Droplet Sizes, Dynamics and Deposition in Vertical Annular Flow

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In Partial Fulfillment

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Doctor of Philosophy in Chemical Engineering

by

José Carlos Brito Lopes

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Droplet Sizes, Dynamics and Deposition in Vertical Annular Flow

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To

My Parents and Madalena

*Eles não sabem, nem sonham
que o sonho comanda a vida.
Que sempre que um homem sonha
o mundo pula e avança
como bola colorida
entre as mãos de uma criança.*

António Gedeão, in "Pedra Filosofal"

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Abstract

The role of droplets in vertical upwards annular flow is investigated, focusing on the droplet size distributions, dynamics and deposition phenomena. An experimental program was performed based on a new laser optical technique developed in these laboratories and implemented here for annular flow. This permitted the simultaneous measurement of droplet size, axial and radial velocity.

The dependence of droplet size distributions on flow conditions is analyzed. The Upper-Log Normal function proves to be a good model for the size distribution. The mechanism controlling the maximum stable drop size was found to result from the interaction of the pressure fluctuations of the turbulent flow of the gas core with the droplet.

The average axial droplet velocity showed a weak dependence on gas rates. This can be explained once the droplet size distribution and droplet size-velocity relationship are analyzed simultaneously. The surprising result from the droplet conditional analysis is that larger droplet travel faster than smaller ones. This dependence cannot be explained if the drag curves used do not take into account the high levels of turbulence present in the gas core in annular flow. If these are considered, then interesting new situations of multiplicity and stability of droplet terminal velocities are encountered. Also, the observed size-velocity relationship can be explained.

A droplet deposition is formulated based on the particle inertia control. This permitted the calculation of rates of drop deposition directly from the droplet size and velocities data. With the rates of deposition and droplet velocities known, the momentum balance equations now can be written to include the droplet exchange terms. It is shown that droplet entrainment can be responsible for a significant part of the total measured pressure drop. The interfacial friction factors calculated from these results are essentially independent of liquid film Reynolds number.

Table of Contents

	Page
Table of Contents	i
List of Figures	iv
List of Tables	ix
Chapter 1. Introduction	1
1.1 Motivation and Relevance of the Problem	1
1.2 An Annular Flow Scenario	4
1.3 Objectives and Dissertation Layout	5
Chapter 2. Experimental Techniques, Data Processing and Statistical Analysis	9
2.1 The Flow Loop and Flow Rate Measurements	9
2.2 Drop Size and Velocity Measurements with a Laser Technique	14
2.2.1 Introduction	14
2.2.2 Basic Principles of The Laser Technique	15
2.2.3 A Geometrical Optics Model of the Laser Technique	26
2.2.3.1 Introduction	26
2.2.3.2 The Optical Path of a Light Ray	27
2.2.3.3 Light Intensity at the Optical Interface	36
2.2.3.4 Light Intensity in Passage Time Slit from Droplet Crossing Laser	39
2.2.4 Simultaneous Measurements of Two Velocity Components . . .	45

2.2.5	Experimental Errors	47
2.2.6	Signal Generation and Detection Equipment	52
2.3	Data Acquisition System	57
2.3.1	Analog Signal Conditioning	57
2.3.2	Digital Processing of the Signals	59
2.3.3	Computer Signal Processing	60
2.4	Data Statistical Analysis	62
Chapter 3. Droplet Sizes in Annular Flow		66
3.1	Introduction	66
3.2	Droplet Size Characterization	72
3.3	Dependence of Drop Size Distribution on Flow Rates and Radial Position	84
3.4	Droplet Break-up Mechanisms. The Critical Weber Number	95
Chapter 4. Droplet Dynamics in Vertical Annular Flow		111
4.1	Introduction	111
4.2	Experimental Data on Velocities of Droplets	116
4.2.1	The Stochastic Nature of the Velocity Vector of a Droplet	116
4.2.2	Axial Velocity of Droplets in Annular Flow	118
4.2.3	Lateral Velocity of Droplets in Annular Flow	125
4.2.4	Dependence of Droplet Velocities on their Sizes	131
4.3	Equation of Motion of a Particle Moving in a Fluid	141
4.3.1	Drag Force on a Particle	146
4.3.2	The Drag Coefficient Curves	153
4.3.3	The Terminal Velocity of Droplets in Annular Flow	162
4.3.4	Prediction of Droplet Velocities at the Center of the Column	173
Chapter 5. Droplet Entrainment and Its Contribution to Momentum Transfer		187
5.1	Introduction	187
5.2	Development of a Deposition Model	188
5.2.1	The Trajectory of a Droplet in the Gas Core	188
5.2.2	Deposition Rate of Droplets	191
5.2.3	A Model for the Angle Volume Density Function	197
5.2.4	Final Form of the Deposition Model	203

5.3 Rates of Droplet Deposition	205
5.3.1 The Relationship Between $W_D(L_D)$ and N_D	205
5.3.2 Prediction and Comparison with Experimental Data	208
5.4 The Linear Momentum Balance Equation. Interfacial Friction Factor	216
Chapter 6. Summary and Suggestions for Future Work	232
6.1 Summary and Conclusions	232
6.2 Suggestions for Future Work	235
Appendix A. Experimental Results	238
A.1 Experimental Conditions at Test Section	239
A.2 Probability Density Function of droplet size, velocities, and angle	240
A.3 Droplet Conditional Analyses	271
Appendix B. FORTRAN 77 Listings of Computer Codes	278
B.1 Listing of Program DIASIM Used for the Simulation of Droplet-Laser Interference	279
B.2 Listing of Program STAT4 Used for the Statistical Analysis of Experimental Results	282
Notation	289
Literature References	297

List of Figures

	Page
1.1 Vertical Upwards Two-Phase Flow	2
1.2 Cross-sectional view of annular flow. From Langner (1978)	6
2.1 Schematic diagram of Vertical Multiphase Upflow Loop	10
2.2 Schematic diagram of air radial injection device	12
2.3 Schematic diagram of water axial injection device	13
2.4 Spatial configuration of laser and light intensity measuring points at Test Section	16
2.5 Characteristic droplet positions relative to the laser and horizontal slit viewing area	18
2.6 Dynamic evolution of Passage Time Signal for a single droplet	19
2.7 Droplet passage time, velocity and diameter relationship	21
2.8 Microscopic photograph of used Ronchi Grating for velocity measurements	23
2.9 Ray diagram for a droplet immersed in the laser beam	24
2.10 Ray diagram for a ray crossing a flat optical interface	28
2.11 Light sources created by an original light source S_o	30
2.12 Information Tree representation of a light ray crossing multiple droplets	31
2.13 Vector diagram for ray reflection on a droplet	33
2.14 Vector diagram for ray refraction on a droplet	35
2.15 Ray diagram for reflection and refraction paths through the droplet	38

2.16	Passage Time Signal trace. Droplets of different sizes and equal velocities	42
2.17	Passage Time Signal trace. Droplets with different velocities and equal sizes	44
2.18	Passage Time Signal trace. Multiple droplets in the viewing area - Multiple Signal	46
2.19	Ronchi Gratings orientation for two orthogonal component velocity measurements	48
2.20	Experimental frequency bands used for axial and lateral velocity measurements	50
2.21	Photograph of laser set-up in test section and grating glass discs . . .	53
2.22	Schematic set-up of grating discs and driving motors	54
2.23	Cross sectional view of column test section radial distribution of experimental measuring locations	56
2.24	Data Acquisition System diagram for droplet size and two velocity components measurements	58
2.25	Photograph of Data Acquisition System equipment and column Test Section	61
2.26	Computer graphic displays of typical Passage Time Signal traces and droplet size and velocities measurements	63
3.1	Evolution of the mean drop diameter with the number of droplets sampled	76
3.2	Number and volume based drop diameter distribution functions . . .	85
3.3	Dependence of the mean drop diameter, $\bar{d}_{10}$, on the flow rates . . .	86
3.4	Dependence of the mean drop diameter, $\bar{d}_{32}$, on the flow rates . . .	87
3.5	Dependence of the maximum detected drop diameter on the flow rates	88
3.6	Dependence of the number drop diameter distribution function on the flow rates	90
3.7	Dependence of the number drop diameter density function on the gas flow rate	92
3.8	Mean film thickness <i>versus</i> the superficial gas velocity. From Zabaras (1985)	94
3.9	Maximum film thickness <i>versus</i> the superficial gas velocity. From Zabaras (1985)	96

3.10	Radial profiles for the mean drop diameter, $\bar{d}_{10}$	97
3.11	Dependence of the number drop diameter distribution function on the radial position	98
3.12	Dependence of the number drop diameter density function on the radial position	100
3.13	Critical Weber number <i>versus</i> the gas velocity	103
3.14	Maximum diameter <i>versus</i> dissipation rate	106
3.15	Theoretical and experimental values of the mean drop diameter, $\bar{d}_{32}$	110
4.1	Experimental Slip ratio <i>versus</i> gas Reynolds number at centerline	121
4.2	Gaussian density function fit of experimental axial velocity p.d.f. Best and worst fit at centerline	124
4.3	Dependence of droplet axial velocity p.d.f. on gas rates for different liquid rates	126
4.4	Average droplet axial velocity radial profiles for different flow rates	130
4.5	Dependence of average radial velocity on flow rates and radial position	132
4.6	Wave undercut mechanism for droplet generation and radial velocity impact	134
4.7	Droplet radial velocity <i>versus</i> droplet size. From Andreussi and Azzopardi (1981)	136
4.8	Droplet axial velocity <i>versus</i> droplet size. From Tong <i>et al</i> (1983)	137
4.9	Experimental droplet axial velocity <i>versus</i> droplet size for different liquid rates and varying gas rates at centerline	138
4.10	Experimental droplet axial velocity <i>versus</i> droplet size for different gas and liquid rates and varying radial position	140
4.11	Simultaneous droplet axial velocities and droplet size distribu- tions for different liquid rates and varying gas rates	142
4.12	The Standard Drag Curve. From Clift <i>et al</i> (1978)	154
4.13	Schematic particle drag curve for a fixed level of turbulence	158
4.14	The particle drag curves for different levels of turbulence intensity	161

4.15	Terminal velocity dependence on droplet size for $u_{rms} = 0$	164
4.16	Bifurcation diagrams of terminal velocity <i>versus</i> droplet size for $u_{rms} = 1.1, 1.2$, and 1.6 m/s	165
4.17	Bifurcation diagrams of terminal velocity <i>versus</i> droplet size for $u_{rms} = 2.0, 2.3$, and 2.4 m/s	167
4.18	Bifurcation diagrams of terminal velocity <i>versus</i> droplet size for $u_{rms} = 2.6, 2.8$, and 3.0 m/s	169
4.19	Force ratio function g_R <i>versus</i> relative velocity for different droplet sizes and fixed turbulence level ($I_R = 2.5 \text{ m/s}$)	171
4.20	Axial velocity <i>versus</i> droplet size predictions at centerline for different levels of turbulence	176
4.21	Droplet axial velocity evolution with radial position for different droplet sizes	178
4.22	Axial velocity <i>versus</i> droplet size predictions at centerline with modified drag curves or different levels of turbulence	180
4.23	The influence of gas rates on droplet axial velocity at centerline	182
4.24	The influence of droplet radial velocity on droplet axial velocity at centerline	183
4.25	The influence of initial droplet velocity on droplet axial velocity at centerline	185
5.1	Droplet trajectories for different values of the initial velocity, $v_z(0)$	189
5.2	Schematic representation of annular flow: the cross reference section, A_{z_0} ; and deposition length, L_D	192
5.3	Schematic representation of a droplet source, and its directional coordinates	194
5.4	Experimental values of average angle, $\bar{\theta}_V$, <i>versus</i> U_{GS} , for different values of U_{LS}	200
5.5	Experimental radial profiles of $\bar{\theta}_V$ for different values of U_{GS} and U_{LS}	202
5.6	Experimental and theoretical angle probability density functions, f_{θ}^V	204
5.7	Fractional deposition, X , <i>versus</i> deposition length, L_D , for different values of $\bar{\theta}_V$	206

5.8	K_D/U_{GS} versus δ^* , as computed from Equation 5.24	209
5.9	Deposition rates of published data (McCoy and Hanratty, 1977), and experimental values from the present work	213
5.10	Experimental curves X versus L_D/D , from Cousins and Hewitt (1968), and theoretical curves from best fit of Equation 5.24	215
5.11	Control volume description for momentum balance in annular flow	217
5.12	Experimental values of ∇p_T , W_{LE} , versus Re_{GS} , from Zabaras (1985)	224
5.13	Various pressure gradient terms in Equation 5.45 versus Re_{GS} , for different values of U_{LS}	226
5.14	Friction factor values, f_i evaluated without entrainment contribution versus $\bar{m}/D$, for different values of Re_{LS}	229
5.15	Friction factor values, f_i , evaluated with and without entrain- ment contribution versus Re_G , for different values of Re_{LS}	230

List of Tables

	Page
3.1 Summary of previous measurements on drop sizes in vertical upwards annular flow	68
3.2 Summary of experimental values of the various mean drop diameters	78
3.3 Summary of the parameters for the number and volume based drop diameter distribution functions	81
4.1 Summary of previous experimental work on the simultaneous measurements of size and velocities of droplets in annular flow . . .	115
4.2 Summary of experimental measurements of axial and slip velocities of droplets in annular flow	119
4.3 Summary of experimental measurements of lateral and radial velocities of droplets in annular flow	128
5.1 Summary of experimental and theoretical statistical parameters for the angle distribution	199
5.2 Summary of values of K_D , based on the experimental data obtained in this work	210
5.3 Summary of published deposition studies in vertical flow	211
5.4 Experimental data in vertical upwards two-phase flow in a 50.8 mm column. From Zabaras (1985)	222

Chapter 1

Introduction

1.1 Motivation and Relevance of the Problem

Consider a long vertical tube into which liquid and gas are being injected simultaneously at the base and flowing upwards. Several flow pattern regimes can be established depending on the particular settings of fluid flow rates where the two phases distribute in a geometrically similar way. If the liquid rate is maintained constant and the gas rate is set at different increasing values, the following sequence of distinct flow patterns can be identified as shown in Figure 1.1:

- A *bubbly flow* pattern exists at low gas rates and consists of a dispersed gas phase in the form of small bubbles moving upwards in a more or less erratic fashion through a continuous liquid phase.
- A *slug flow* pattern results from the increasing volume fraction occupied by the bubbles with coalescence and formation of large bullet-shaped bubbles usually designated as Taylor bubbles. A stable topological structure is present with

FLOW PATTERNS IN VERTICAL FLOW

Figure 1.1
Vertical Upwards Two-Phase Flow Patterns.

Taylor bubbles alternating with liquid slugs and flowing upwards in a more or less stable fashion. The liquid phase still forms a continuous phase.

- A *churn flow* pattern appears at larger gas flow rates and results from the unstable nature of the liquid slugs traveling now at higher velocities. When the liquid slug breaks, a rather chaotic unstable regime is observed with liquid moving upwards and downwards and the gas moving upwards in a pulsatile type fashion.
- Finally, an *annular flow* pattern appears at high gas rates. Two continuous phases and one dispersed phase are present: one continuous liquid phase in the form of a wavy film over the internal walls of the pipe; one continuous gas phase constituting a *gas core* bounded laterally by the liquid film surface; and one dispersed liquid phase in the form of spherical droplets entrained by the gas core.

Early approaches to the modelling of two-phase flow ignored the presence of distinctly different flow patterns (Lockhart and Martinelli, 1949, and Dukler *et al.* ,1964). But these were based largely on empirical evidence to create useful correlations.

In recent years it has been recognized that a more satisfactory research strategy is to focus on each flow pattern separately (Dukler and Taitel, 1984). Considerable advances have been reported for slug flow (Fernandes *et al.* ,1983). Bubbly flow has also been studied extensively and the concepts are relatively straightforward (Ishii and Zuber, 1979). However, annular flow has until now been a relatively unexplored flow pattern despite the fact that it is an important flow regime.

The annular flow pattern can occur in many cases of important industrial

operations. For instance: in the evaporators and condensers of conventional power-generating plants; in pressurized water reactors of nuclear power plants during a loss of coolant accident; in geothermal wells, gas-oil wells, gathering systems and pipelines. It is also found in chemical reactors, direct fired heaters, spray contactors, and in many other operations of the process industry.

The ability to understand and model annular flow is of central importance to reliable design and scale-up of equipment of the type discussed above. The safety and reliability of equipment operations is also strongly affected by the degree of knowledge about annular flow, since the design of adequate control strategies is not possible without adequate models.

Beside these important practical reasons for studying annular flow there are significant intellectually challenging fundamental aspects of scientific interest. In annular flow many interesting basic problems are as yet unresolved: the study of the dynamics and stability of droplets in turbulent flows; the dynamics of free-moving surfaces of liquid films; and the turbulence structure of flow fields contained by non-rigid surfaces and interacting with freely suspended particles.

A more realistic picture of the problems involved in annular flow research can only be obtained after a description or visualization of the actual physical scenario present in a column when operated under this regime.

1.2 An Annular Flow Scenario

A typical picture of an annular flow scenario can be found in Figure 1.2 where a cross-sectional view of a pipe operating at this flow regime is presented (Langner,

1978).

A main characteristic of annular flow is the presence of high gas velocities and low average liquid velocities. The liquid moves upwards as a continuous thin film over the internal walls of the pipe and as droplets in a continuous gas core. The droplets originate from large disturbance waves in the liquid film. They are injected into the gas core, accelerated by it to reasonably high velocities compared with the slow moving liquid film, travel through it, and end-up depositing back on the liquid film. The droplets are mostly spherical and the large unstable droplets are subject to break-up inside the gas core generating new stable spherical droplets.

A characteristic common to all the phases is the high local degree of unsteadiness despite the fact that the gas and liquid are injected into the operating column at constant steady rates. Highly turbulent gas core and liquid films are present, being constantly interfered with by droplets being formed and deposited.

It is exactly these high degrees of unsteadiness, turbulence and complexity which are responsible for the actual lack of full understanding of annular flow, mostly because they make it impossible to use simple experimental techniques and require the development of new methods of measurements, as in the case of the present work, to create the data necessary to improve an understanding of the process.

1.3 Objectives and Dissertation Lay-Out

It was the objective of this research to explore both experimentally and theoretically the nature of droplet flow in the gas core of two-phase annular flow. This

Figure 1.2
Cross-sectional view of annular flow. From Langner (1978).

study is restricted to *equilibrium annular flow* which exists at far enough distance from the tube base that droplet deposition and entrainment rates are equal.

An experimental program was performed based on a new optical method for obtaining simultaneous measurements of droplet size and axial and radial velocity components. This method developed in these laboratories by Semiat and Dukler (1981) required extensive development to make it useful for annular flow. The technical aspects of such an experimental method and other related experimental details are presented in Chapter 2.

In Chapter 3 the results on droplet sizes and their dependence on flow conditions are presented. Also, the stability of large droplets is studied and several possible break-up mechanisms are tested against the new data and a recommendation is advanced.

In Chapter 4 data on droplet axial and lateral velocities is presented. The droplet-gas slip velocity dependence on flow conditions is studied. A droplet formation mechanism is proposed which explains the radial velocities detected. To understand the droplet velocity-size dependence observed experimentally, a careful analysis of the droplet dynamics equations is made. The influence of turbulence and other flow parameters on the droplet drag curves are analyzed. Terminal droplet velocity computations and dynamic simulations of droplet trajectories are presented which explain the observed droplet velocity-size dependence.

In Chapter 5 a model is introduced which permits the computation of droplet mass transfer coefficients in annular flow based on data of simultaneous measurements of droplet size and two velocity components. Once the mass transfer coefficients are determined and combined with data on droplet velocities and sizes, an

analysis can be made of the importance of the droplets in the process of momentum transfer.

Finally in Chapter 6 the conclusions of this work are summarized and suggestions are made for future experimental and theoretical work.

Chapter 2

Experimental Techniques, Data Processing and Statistical Analysis

2.1 The Flow Loop and Flow Rate Measurements

The flow loop used for the experiments in this work is represented schematically in Figure 2.1. The test section consists of a 10 *m* long vertical column with an internal diameter of 50.74 ± 0.18 *mm* and a nominal wall thickness of 6.4 *mm*. The column material was transparent Plexiglas to enable visualization of the internal flow.

The vertical column was a part of a flow loop consisting of a closed water circuit and an open loop air circuit. The water was delivered by means of a centrifugal pump with a total discharge head of 141 *m*, and driven by a 3 *Hp* motor. The water circuit passed through a heat-exchanger to keep the liquid temperature constant during the experiments. The air was supplied from a central compressed air line for the low gas rates and from two compressors in series for the largest gas rates. The

Figure 2.1
Schematic diagram of Vertical Multiphase Upflow Loop.

air was separated from water condensate before injection in the circuit through the use of two high efficiency air-water separators in series.

Both air and water were injected at the bottom of the column. First, the air was injected radially in a uniform way through an injection device as represented in Figure 2.2. The air passed through a calming section with a length equivalent to 17.5 column diameters. Then the water was injected in the axial direction, around the inside pipe wall, through the device represented in Figure 2.3.

This water injection device was designed to minimize the entrance effects of the gas and liquid injection in the column. Observe that water was injected through an annulus of 2.38 mm gap, which size is of the order of magnitude of the average film thickness, $\bar{m}$. Thus, most of the water is accelerated before the injection point where water and air are in contact. In this way both fluids are already moving in the prevailing directions and velocities in annular flow, and an *equilibrium annular flow* situation is attained in a very short distance. Also, this type of injection avoids the creation of very fine droplet sprays when one of the fluids is injected into the other in a direction normal to the flow.

The experimental measurements of droplet sizes and velocities were made at a distance of 8.9 m from the gas injection point, giving an equivalent distance of 175 pipe diameters. Therefore, in this way, the existence of any entrance effect was minimized.

The air and water were separated at the top of the column using a gas-liquid separator. Then, the water was recirculated and the air vented into the atmosphere.

The air flow rate was measured with a calibrated orifice meter having a maximum expected uncertainty of 3% as indicated from the calibration curve. The water

Figure 2.2

Schematic diagram of air radial injection device.

Figure 2.3
Schematic diagram of water axial injection device.

flow rate was measured using a rotameter, with a maximum uncertainty of 3% from the calibration curve.

Both temperature and pressure were monitored at the measuring location. The values of pressure, mass flow rates, superficial velocities, Reynolds numbers, and the radial position of measurements for the 22 experiments realized, are reported in Table A.1 in Appendix. The values of densities and viscosities used in the calculations were adjusted for pressure and temperature for each experiment.

The experiments listed in Table A.1 are given in chronological order. In other tables in this paper the order of listing of experiments is changed, but the experiment number is maintained throughout.

2.2 Drop Size and Velocity Measurements with a Laser Technique

2.2.1 Introduction

The main experimental goal of this work was to be able to measure simultaneously the size and velocity vector of drops in vertical upwards annular flow. The basic characteristics of these droplets are that they are moving at relatively high velocities (from 5 m/s to 30 m/s), and have a wide spectrum of sizes (100 μm to 3 mm).

The basic optical technique for simultaneous measurement of bubble or drop size and velocity was developed by Semiat and Dukler (1981). In their paper the

basic principles of the method are explained. In the next part of this chapter the principles will be reviewed from the perspective of applying them to the specific goal of this work and improvements made in the method are described based on a careful optical analysis. The design and use of a new data acquisition system is presented.

2.2.2 Basic Principles of The Laser Technique

The experimental technique consists, basically, in the measurement of the time varying intensity of light at two points in space. The light intensity oscillations are created by the crossing of a laser beam by a transparent or reflecting particle. In this study the particles are transparent, nearly spherical liquid droplets traveling in the gas core of an annular flow regime. The presence of a wavy film on the walls of the column required a special method to penetrate the film with the laser beam as shown in the schematic of Figure 2.4.

The laser beam had to be introduced in the gas core, through the pipe wall to avoid interference from the liquid film. In this study, a $1200\ \mu\text{m}$ diameter beam from a $15\ \text{mW}$ He-Ne laser was introduced by means of a $3000\ \mu\text{m}$ diameter quartz-rod with flat polished ends and $4\ \text{cm}$ long. The rod was positioned to allow a clearance of $7500\ \mu\text{m}$ from the intended point of droplet measurements.

The first point of light intensity measurements was positioned just in front of the incident beam. Light intensity was measured through a $75 \times 2000\ \mu\text{m}$ rectangular slit positioned normal to the direction of the gas flow. The light passing this slit was carried by an optic fiber ribbon to a photomultiplier, PM1.

Figure 2.4
Spatial configuration of laser and light intensity measuring points at Test Section.

The second measuring point was positioned in front of an incident beam, but now at a 38° angle to the horizontal. Light was measured through a $800\ \mu\text{m}$ pinhole. A cylindrical optic fiber recessed in a hollow metallic tube supporting the pinhole carried the light to a photomultiplier, PM2. This scheme of recessing the optic fiber inside a tube with an internal black surface, enabled control over the measuring volume. In the experiments it consisted of the volume, centered at the tube axis at 38° angle, resulting from the intersection of the $1200 \times 75\ \mu\text{m}$ viewing region of the laser with an almost cylindrical viewing cone of $1100\ \mu\text{m}$ diameter. This resulted in a measuring volume with an oval cross section with principal axis dimensions of $1100 \times 1786\ \mu\text{m}$ and $75\ \mu\text{m}$ thick, enabling the performance of local measurements. Only particles passing through this region could be detected simultaneously by PM1 and PM2.

The photomultiplier, PM1, created a time dependent signal which will be referred to as the *passage time signal*. Consider a droplet of diameter, d , traveling with a velocity vector, $\underline{v}$, in a zx -plane that contains the laser beam axis. The center of the viewing slit will be positioned at z_s , and the slit has a width of s . Five characteristic positions of the droplet relative to the laser beam are represented in Figure 2.5. They correspond to situations where: 1^- , the droplet has not yet entered the laser region; 2^- , the droplet is immersed in the laser beam but not yet in front of the viewing slit; 3, the droplet is in front of the slit beam; and 2^+ and 1^+ equivalent to 2^- and 1^- , respectively, but now after crossing the slit beam region.

Figure 2.6-a is a plot of the position of the droplet center, z_p , versus time. The radius of the laser beam is $600\ \mu\text{m}$. The five typical situations are again depicted in this graph. Figure 2.6-b represents the relative light intensity, I/I_0 , as

Figure 2.5
Characteristic droplet positions relative to the laser and horizontal slit viewing area.

Figure 2.6
Dynamic evolution of Passage Time Signal for a single droplet.

measured from PM1 where I_0 corresponds to the light intensity measured without droplet interference. For situations 1^+ and 1^- , the relative intensity is unity. As the droplet progresses into the laser region, as in 2^+ and 2^- , the slit is still receiving the full amount of light, but now it is possible that additional light is received by means of reflection or refraction of light from the droplet. In this case the relative intensity can be larger than unity. When the droplet moves into the viewing area in front of the slit, then the light intensity drops below unity achieving a minimum at the point where the droplet position z_p is equal to z_s . After this point the signal evolves in a symmetric way relative to the instant of the minimum. This evolution determines for every droplet at any velocity a given characteristic passage time, τ_{PT} , equal to the time interval between the instants when the passage time signal, I/I_0 , falls below unity.

The relationship between τ_{PT} and the velocity, $\underline{v}$, and diameter, d , of the droplet can be obtained from analysis of Figure 2.7, where L_{PT} is the distance travelled by the droplet while immersed in the viewing region, and $||\underline{v}||$ is the droplet speed. The relationship is:

$$\tau_{PT} = \frac{L_{PT}}{||\underline{v}||} = \frac{d + s}{||\underline{v}|| \cos \theta} = \frac{d + s}{v_z}, \quad (2.1)$$

where v_z is the droplet axial velocity, and θ is the angle off the vertical axis. Therefore, if τ_{PT} and v_z are measured, then it is possible to determine the droplet size, d .

The droplet axial velocity, v_z , was determined by measuring the frequency of drop passage across a series of alternating planar regions of light and dark fringes created by passing the the laser beam through a Ronchi grating supported on a

Figure 2.7

Droplet passage time, velocity and diameter relationship.

circular transparent glass plate placed normal to the laser beam before introducing it in the column as shown in Figure 2.4. This type of grating consists of very precisely ruled alternating transparent and opaque fringes set on a glass. A microscopic photo of the actually grating used is presented in Figure 2.8, where the fringe spacing is $s_F = 50 \mu m$. The supporting disc had a total of 4098 fringes uniformly distributed radially. The laser beam passing through the Ronchi grating will produce a continuous series of parallel planes of alternating dark and light regions on the other side of the grating, with a spacing equal to the fringe spacing on the grating.

Figure 2.9 is a ray diagram of the laser beam having passed through a Ronchi grid and being intercepted by a droplet moving upwards. The edges of the light and dark planes are designated as lines $A_1, A_2, B_1, B_2, C_1, C_2, etc.$ At an instant, t , the drop is located as shown. Follow the rays K_2 and L_2 which delineate a region of light as they intercept the surface of the drop as shown. Part of the light is refracted and leaves the drop at the other side, as indicated by K_6 and L_6 . If the pinhole in front of PM2 is located at the plane $z_1 - z_2$, one would observe on this pinhole at time, t , an array of light and dark fringes delineated by the intersections of rays $E_6 - M_6$.

If the droplet is moving through a laser beam whose axis is stationary, and because the interference surface is translated upwards, one would observe the fringes moving across the slit area at exactly the same frequency at which they are being intercepted by the droplet as it passes through the laser beam. Therefore, the output of PM2, which will be called the velocity signal, will have a frequency, f_M ,

Figure 2.8
Microscopic photograph of used Ronchi Grating for velocity measurements.

Figure 2.9
Ray diagram for a droplet immersed in the laser beam.

equal to:

$$f_M = \frac{v_z}{s_F} . \quad (2.2)$$

If the grating is moved at a constant axial velocity, v_G , then the previous analysis is still valid, but now it has to be done from a moving frame of reference. The difference is that now the light and dark regions are moving with a constant speed relative to the fixed pinhole and the frequency observable from PM2 is given by:

$$f_M = \frac{v_G}{s_F} + \frac{v_z}{s_F} = f_G + \frac{v_z}{s_F} , \quad (2.3)$$

where f_G is the frequency due to the moving fringes in the absence of drops. The difference between the two frequencies is usually called the *Doppler shift* and expressed as:

$$f_M - f_G = \frac{v_z}{s_F} . \quad (2.4)$$

The Doppler shift can be positive or negative depending on the relative direction of the moving particle relative to the laser beam.

Hence, if the grid spacing, s_F , and the speed of rotation of the grating, v_G , are known, and the passage time, τ_{PT} , and the frequency, f_M , are measured from the output of photomultipliers, PM1 and PM2, then it is possible to compute from these data the droplet diameter, d , and the droplet velocity, v_z , by the use of the relationship expressed by Equations 2.1 and 2.4. This constitutes the basic working principle of this new laser technique.

As a practical matter the passage time signal is seldom well defined as the idealized picture shown in Figure 2.6. Furthermore, in many instances a second particle enters the optical sample space while the first particle is in passage. One

possibility is to reject all signals except those which are clearly understood. However this results in very low data acquisition rates. As will be shown in the next section, applying principles of geometrical optics makes it possible to interpret less ideal passage time signals and this derives useful data in such a way which increases data acquisition rates substantially.

2.2.3 A Geometrical Optics Model of the Laser Technique

2.2.3.1 Introduction

The objective of this particular study was to analyze some characteristics of the passage time and the velocity signal as measured in the experiments. In particular it was considered necessary to understand the shape of the signals when transparent droplets travel through the laser beam and the effect on the signal shape when more than one droplet is present, a frequently occurring situation in these experiments.

Basically, it is necessary to find the light distribution in space resulting from the interference of a bundle of rays, created by the Ronchi grating, with a spherical droplet. Since the thickness of the light rays and the droplet size, ($d > 100 \mu m$), are several orders of magnitude larger than the characteristic wavelength of the laser beam, the theoretical tools necessary to the model are considerably simplified and it is possible to use the principles of geometrical optics. Diffraction patterns resulting from wave interference phenomena are present, but they do not interfere with the use of the method. The few important aspects of diffraction will be analyzed in Section 2.2.5. Only a two-dimensional analysis will be necessary due to the symmetric characteristic of the droplets.

The light intensity at the slit of PM1 (see Figure 2.4) at any instant, t , depends on the number of light rays impinging on the slit and on the particular intensity of each one. The rays originate at the Ronchi grating and reach the slit in two distinct ways: either directly from the laser beam directed toward the slit or by means of reflection and refraction with one or more drops immersed in the beam with a ray eventually impinging on the slit.

To determine the light intensity at PM1 at any particular time the droplet positions are fixed and each single ray emerging from the laser beam will be followed for possible reflections and refractions with one or more drops, as explained in Section 2.2.3.2. The light intensity of each ray impinging on the slit will be computed according to the methods presented in Section 2.2.3.3. Finally, the light intensity at PM1 is computed as in Section 2.2.3.4. Time is incremented, the droplets are allowed to move to a new configuration depending on their velocity vectors, and the process is repeated again for a number of times necessary to obtain a complete picture of the evolution of the passage time signal.

2.2.3.2 The Optical Path of a Light Ray

After the laser beam crosses the Ronchi grating an alternating distribution of the light and dark regions contained between parallel planes is created. These light regions will be modeled, from now on, as light rays obeying the laws of geometrical optics.

The objective here is to set up the equations which, given a certain initial position of the ray source, will enable the ray path to be determined when it crosses a transparent circular particle. At the point of intersection, the incident ray, with

$$\theta_i = \theta_r : \text{Reflection's Law}$$

$$n_i \sin \theta_i = n_t \sin \theta_t$$

Snell's Law

Figure 2.10

Ray diagram for a ray crossing a flat optical interface.

an angle, θ_i , from the normal at that point as shown in Figure 2.10 will originate a reflecting ray with an angle, θ_r , from the normal, so that:

$$\theta_i = \theta_r \quad (\text{Reflection law}) , \quad (2.5)$$

and a refracted ray, that crosses the interface at an angle, θ_t , so that:

$$n_i \sin \theta_i = n_t \sin \theta_t \quad (\text{Snell's law}) , \quad (2.6)$$

where n_i and n_t are the refractive indexes of the incidence medium and transmittance medium, respectively (for air $n_{Air} = 1.0$ and for water $n_{H_2O} = 1.33$). The particular values that n_i and n_t take depend on the propagating medium.

Consider a single ray originating at the laser with two transparent liquid droplets in front of its path as depicted in Figure 2.11. From the original light source, S_o , at the original laser beam a set of new light sources is created for each ray intersection with a particle. For the first intercepted particle a reflection source, S_{r1} , and a diffraction source, S_{d1} , and for the second particle the sources, S_{r2} , and, S_{d2} , are created respectively. Additional rays created by internal reflections will be neglected since the intensity of the ray decays very rapidly with multiple reflections. The position of each source can be identified by its cartesian coordinates (x, z) . An additional coordinate, γ is necessary to specify the direction of the ray coming out of the source, as the angle between the ray and the x -coordinate measured counterclockwise.

The path of the original ray can be followed using a *tree type analysis*. Figure 2.12-a shows the actual tree originated from a single, original ray after intersection with several particles. Each horizontal level of the tree represents a possible intersection with a particle. For instance, the source, S_{d3} , results from the reflection

Figure 2.11

Ligth sources created by an original light source S_0 .

Figure 2.12
Information Tree representation of a light ray crossing multiple droplets.

source, S_{r2} , which was obtained from the refraction source, S_{d1} , of the original ray, S_o . Each source has its own coordinates associated with each particle present. A convenient index tree associated with the previous information tree is presented in Figure 2.12-b. With each source there is associated a single integer number, J . If J is even, then the source is a reflection source, S_r , and, if it is odd, the source is a diffraction source, S_d . The source related to index, J , was originated from another source with an index equal to the largest integer less than or equal to $J/2$. In this way, it is possible to follow the path of the ray with simple logic and algebra and from this point on only this index will be used to identify the light sources.

For any given source, S_J , with coordinates (x_J, z_J, γ_J) , it is necessary to determine if the ray emerging from it will find a particle in its path. To this end, the system of the linear equation supporting the light ray, together with the quadratic equation of the circle with center coordinates (x_p, z_p) and diameter d , has to be solved simultaneously, and this has to be done for all the particles present.

If a solution exists, the one corresponding to the closest point to the source S_J is chosen, with coordinates obtained directly from the solution (x_{2J}, z_{2J}) and with γ_{2J} to be determined. This angle will depend on γ_J and on θ_i , the incidence angle. If $\underline{S}$, $\underline{I}$, $\underline{P}$ are the position vectors of the source S_J , the source S_{2J} , and the particle center (x_p, z_p) , respectively, then θ_i can be found directly from the definition of inner product of the vector difference $(\underline{I} - \underline{S})$ and the vector difference $(\underline{P} - \underline{I})$, as:

$$\cos \theta_i = \frac{(\underline{I} - \underline{S}) \cdot (\underline{P} - \underline{I})}{\|\underline{I} - \underline{S}\| \|\underline{P} - \underline{I}\|} \quad (2.7)$$

These two difference vectors can be found represented in Figure 2.13. In the same figure, it is observed that θ_i contributes to the determination of γ_{2J} in two

Figure 2.13
Vector diagram for ray reflection on a droplet

basically different ways, depending on the relative direction of the incident ray and the particle position. In other words, it depends on whether the ray is facing to the right or the left of the connecting line between the source S_J and the particle center (x_p, z_p) .

This *right and left* relationship can be fully characterized once the point (x_c, z_c) of the interception of the line segment between γ_{2J} and (x_p, z_p) at the droplet surface is found. The general relationship between γ_{2J} and γ_J can be found to be:

$$\gamma_{2J} = \gamma_J + \pi + 2\theta_i \text{SIGN}[(x_J - x_c)(z_p - z_c)] = \beta, \quad (2.8)$$

where, SIGN is just an operator that keeps the sign of the argument expression. If the domain of γ_{2J} is restricted to the interval $[0, 2\pi[$, and using the INT operator, that computes the largest integer contained in its argument, then:

$$\gamma_{2J} = \beta - 2\pi \text{INT} \left[\frac{\beta}{2\pi} \right], \quad (2.9)$$

where β is found through equation 2.8. Therefore, if θ_i is determined by Equation 2.7 and the coordinates (x_c, y_c) are computed, then once the coordinates of S_J and of the particle are known, it is possible to compute γ_{2J} . Once the coordinates of S_J and S_{2J} are computed, the remaining problem is to compute the coordinates of S_{2J+1} , the refracting source.

The coordinates of the source of diffracted light (x_{2J+1}, z_{2J+1}) can be easily determined once the angle of the refracted ray, $S_{2J,t}$, emerging from source S_{2J} and traveling inside the particle is found. From Figure 2.14, it is found that:

$$\gamma_{2J,t} = \gamma_{2J} + (\pi - \theta_i - \theta_r) \text{SIGN}[(x_J - x_c)(z_p - z_c)], \quad (2.10)$$

Figure 2.14

Vector diagram for ray refraction on a droplet

where θ_r is obtained from Snell's law (Equation 2.6), and γ_{2J+1} , can be found through:

$$\gamma_{2J+1} = \Psi - 2\pi \text{INT} \left(\frac{\Psi}{2\pi} \right), \quad (2.11)$$

where

$$\begin{aligned} \Psi = \gamma_{2J} + (\pi - \theta_i - \theta_r) \text{SIGN} \left[(x_J - x_c)(z_p - z_c) \right] \\ + (\theta_i - \theta_r) \text{SIGN} \left[(x_J - x_c)(z_p - z_c) \right]. \end{aligned} \quad (2.12)$$

Therefore, if an original source ray is chosen, then Equations 2.5 through 2.12, will enable the computations of all reflected and refracted sources created by the interference with any number of particles. Once all these coordinates are set, then it can be determined if any of the rays impinge on any predetermined viewing area. For instance, the slit region of the passage time signal.

In the computer program listed in Appendix B.1, called DIASIM, there is included a subroutine, RAYSIM, where the previous procedure was implemented. In this subroutine, starting from a source, S_o , positioned in the laser source, the flat end of the quartz rod, all the possible rays are analyzed, and, finally, the intensity of the rays impinging on the viewing slit of passage time signal is found. The intensity computations are based on the expressions developed in the next section.

2.2.3.3 Light Intensity at the Optical Interface

In this case of the planar harmonic light ray impinging on a flat interface of the two dielectric media, the ratio of the reflected intensity to the incident intensity, I_r/I_i , and the ratio of the refracted intensity to the incident intensity, I_t/I_i , can both be derived from the Fresnel's equations (Durst *et al.* 1976) combined with

Snell's law, resulting in:

$$\frac{I_r}{I_i} = \left(\frac{E_{or}}{E_{oi}} \right)^2 = \left[\frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)} \cos \theta_i \right]^2 + \left[\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)} \sin \theta_i \right]^2, \quad (2.13)$$

and

$$\begin{aligned} \frac{I_t}{I_i} &= \left(\frac{E_{ot}}{E_{oi}} \right)^2 \\ &= \left[4 \left(\frac{\sin 2\theta_t}{\sin 2\theta_i} + 1 \right)^{-2} \cos^2 \theta_i + 4 \left(\frac{\tan \theta_i}{\tan \theta_t} + 1 \right)^{-2} \sin^2 \theta_i \right] \frac{\tan \theta_t}{\tan \theta_i}, \end{aligned} \quad (2.14)$$

where E_{or} , E_{ot} , and E_{oi} are the electric field intensity for the reflected, refracted and incident rays respectively.

For a ray originated from a source, S_J , with intensity I_{S_J} , a source, S_{2J} is created with an intensity ratio, $I_{S_J}/I_{S_{2J}}$, given by Equation 2.13.

For the ray emanating from the refraction source, S_{2J+1} , the initial ray went through two interface crossings before emerging out of the spherical particle. Therefore, the ratio, $I_{S_{2J+1}}/I_{S_J}$, can be computed from:

$$\frac{I_{S_{2J+1}}}{I_{S_J}} = \frac{I_{S'}}{I_{S_J}} \frac{I_{S_{2J+1}}}{I_{S'}}, \quad (2.15)$$

where $I_{S'}$ is the intensity of the refracted ray in the first crossing (see Figure 2.15).

Applying Equation 2.15 twice, with the proper values of θ_i and θ_t , then:

$$\begin{aligned} \frac{I_{S_{2J+1}}}{I_{S_J}} &= 4 \left[\left(\frac{\sin 2\theta_t}{\sin 2\theta_i} + 1 \right)^{-2} \cos^2 \theta_i + 4 \left(\frac{\tan \theta_i}{\tan \theta_t} + 1 \right)^{-2} \sin^2 \theta_i \right] \\ &\quad \times \left[4 \left(\frac{\sin 2\theta_i}{\sin 2\theta_t} + 1 \right)^{-2} \cos^2 \theta_t + 4 \left(\frac{\tan \theta_t}{\tan \theta_i} + 1 \right)^{-2} \sin^2 \theta_t \right], \end{aligned} \quad (2.16)$$

which is the product of two terms functionally equivalent to the right-hand-side of Equation 2.14, but with the angles θ_i and θ_t switched in each term. Since for a

Figure 2.15
Ray diagram for reflection and refraction paths through the droplet.

circular region, as in Figure 2.15, for any angle, θ_i , of the incident ray, the refraction angle, θ_t , of the refraction source is the same as θ_i , if Snell's law determines the angles in each surface crossing.

Therefore, for any given source, S_J , if its associated ray intercepts a transparent particle in its way, the angles θ_i and θ_t can be computed as the previous section, and now also the amplitude of the resulting rays can be evaluated through the use of Equations 2.13 through 2.16. These computations are also implemented in subroutine RAYSIM of program DIASIM in Appendix B.1.

2.2.3.4 Light Intensity in Passage Time Slit from Droplet Crossing Laser

From the two previous sections it is now possible to follow for a single ray its geometrical and intensity path when it intercepts a droplet. In the real experiment there is not a unique ray but series of them that can interfere with the droplet. This series of equally spaced rays results from the crossing of the laser through the Ronchi grating. Therefore, the ray spacing will be equal to the fringe spacing, s_F . The number of rays to consider should be equal to the number of fringes crossed by the 1200 μm laser, in a number of 24 in this case. The sources for these rays, $S_o^i, i = 1, \dots, 24$, have fixed x_0^i and γ_0^i coordinates, both equal to zero, and time dependent z^i -coordinates. This dependence on time results from the translation of the grating, imposing a constant frequency, f_G , on the light intensity and can be expressed as:

$$z_0^i(t) = s_F \text{FRAC} \left[(s_F f_G t) / s_F \right] + (i - 1)s_F, \quad i = 1, \dots, 24, \quad t \geq 0. \quad (2.17)$$

where FRAC is the fractional part of the ratio of the two arguments. Therefore, for

a particular instant, t , the z -coordinates of all original sources, S_o^i , can be computed through Equation 2.17.

The light intensity function, $I(x, z, t)$, will assume the following form, for $x = 0$:

$$I(0, z, t) = I_o \delta(z - z_o^i(t)) , \quad i = 1, \dots, 24 , \quad (2.18)$$

where, δ , is the Dirac Delta Function, I_o a constant original intensity, and z_o^i are given by Equation 2.17.

The final objective is to find $I(x, z, t)$ in the region of x and z values corresponding to a region of light intensity measurements by a photomultiplier. In the case of the slit of PM1 for the passage time signal, this corresponds to the region at $x = x_S$ and $z_S - s/2 \leq z \leq z_S + s/2$, where s is the slit size and z_S is the slit center z -coordinate. For PM1, in particular, $x_S = 15000 \mu m$, $s = 75 \mu m$, and $z_S = 600 \mu m$.

If it is assumed that the rays impinging on the slit region are not coherent anywhere, since they travelled different paths, then the intensity, I_{PM1} , at PM1, for any instant, t , can be given by:

$$I_{PM1}(t) = \frac{1}{S} \int_{z_S - S/2}^{z_S + S/2} I(x_S, z, t) dz . \quad (2.19)$$

If $I_{PM1}^0(t)$ represents the intensity observable if no particle was present in the laser region, then a convenient dimensionless relative intensity, I_{PM1}^* , can be defined as:

$$I_{PM1}^*(t) = \frac{I_{PM1}(t)}{I_{PM1}^0} . \quad (2.20)$$

This function can be computed by means of program DIASIM, presented in Appendix B.1. In this program, for any fixed time, t , the program computes the

particles positions, and for all the 24 rays, the subroutine RAYSIM computes their paths and determines if they impinge on the slit region of PM1 and their respective intensity. Then, the main program computes I_{PM1} through Equation 2.19, and $I_{PM1}^0(t)$ is computed by using RAYSIM without particles present. The time variable, t , can be varied automatically by constant increments, Δt_D , and time traces of I_{PM1}^* can be obtained as the ones presented in Figure 2.16.

Figure 2.16 presents the passage time signal, I_{PM1}^* , obtained when a series of three droplets of different diameters ($d_1 = 70 \mu m$, $d_2 = 105 \mu m$, and $d_3 = 140 \mu m$), equally spaced in a row with a separation gap of $200 \mu m$ between each other, and all traveling with the same velocity, $v_z = 5.0 \text{ m/s}$. A clear signal is obtained for each one, and the width of the signal is proportional to the particle diameter in these cases. I_{PM1}^* is observed to be sometimes greater than unity, but with deviations much smaller than the ones experienced in the other direction, when the particles are immersed in the viewing regions. The grating rotation was equivalent to a grating frequency, $f_G = 1 \text{ MHz}$. It is also important to observe that when the droplet is immersed in the viewing area and totally blocks the slit, then the signal intensity drops almost immediately to zero.

Figure 2.17 shows the results now for three equal size particles, $d = 100 \mu m$, but now starting from the same initial z -position and with three different velocities ($v_{z1} = 10 \text{ m/s}$, $v_{z2} = 5 \text{ m/s}$, and $v_{z3} = 3 \text{ m/s}$). In these cases the width of the signals observed are proportional to the particle velocity. Again the particles are simultaneously immersed in the laser, but not simultaneously in front of the slit, therefore, individual signals are found for each particle.

Figure 2.18 presents the results for the case of three particles of different sizes,

Figure 2.16
 Passage Time Signal trace. Droplets of different sizes and equal velocities.

($d_1 = 50 \mu m$, $d_2 = 100 \mu m$, and $d_3 = 70 \mu m$) traveling with the same velocity, $v_z = 5.0 \text{ m/s}$, but now spaced in such a way that there exists the possibility of having more than one particle in front of the slit region at the same time. It is clear there, that information on the passage time, τ_{PT} , for each droplet is not directly obtained from the passage time signal for all of them. But, for the first and last particle it is possible, if the passage time is estimated from the first half signal of the first particle and the last half signal of the third particle, since the passage time associated with the half-signal has a passage time equal to $\tau_{PT}/2$. Therefore, if the individual signals are resolved enough in the multiple signal, it is always possible to obtain passage time values, τ_{PT} , for the first and last particle of the multiple signal. This proved to be of considerable importance in the real experiment, since it was found that the probability of having multiple signals was very high, but afterwards it was still possible to obtain information in these cases.

The program was run for different values of the input parameters and even modified for obtaining the signal at PM2. The basic conclusions of the results can be summarized as:

- For spherical droplets the signal of single particles is symmetric and with an amplitude much larger than the oscillations due to the grating translation. This symmetric characteristic of the single signal enables the evaluation of passage times of the droplets, even in the case of multiple droplets in front of the slit of PM1.
- From the velocity signal traces, the important observations were that the velocity signal is always observable at PM1 when the corresponding passage time signal is evolving, i.e., always contained in the time between the beginning and

Figure 2.17

Passage Time Signal trace. Droplets with different velocities and equal sizes.

the end of the passage time signal.

The implication of these two conclusions from the model results were afterwards implemented in the computer programs that processed the digital versions of the passage time signal and the velocity signals.

2.2.4 Simultaneous Measurements of Two Velocity Components

In Section 2.2.2 the basic principles for measurement of a velocity component was explained. The observed frequency, f_M , depended for a given fringe spacing, s_F , solely on the velocity component in the direction normal to the fringe orientation. Therefore, if a Ronchi grating is oriented in such a way that the fringes are normal to the axial direction of the working frame of reference, then the oscillating light frequency is directly related to v_z . If the fringes are normal to the lateral y -direction, then the frequency is related to the lateral component, v_y .

If the laser beam is made to cross two successive Ronchi gratings with the same fringe spacing, s_F , (see Figure 2.19) oriented in directions normal and parallel to the axial direction, and which are made to rotate at two different speeds, v_{Gz} and v_{Gy} , then the light oscillations will be composed of two harmonics with frequencies f_{Gz} and f_{Gy} , where:

$$f_{Gz} = \frac{v_{Gz}}{s_F} , \quad (2.21)$$

and

$$f_{Gy} = \frac{v_{Gy}}{s_F} . \quad (2.22)$$

A particle moving across the beam with velocity components, v_z and v_y , will

Figure 2.18

Passage Time Signal trace. Multiple droplets in the viewing area
 - Multiple Signal.

shift these frequencies according to Equation 2.3 as:

$$f_{Mz} = f_{Gz} + \frac{v_z}{s_F} , \quad (2.23)$$

and

$$f_{My} = f_{Gy} + \frac{v_y}{s_F} . \quad (2.24)$$

Hence, if in the signal measured by photomultiplier, PM2, these two frequencies of the light oscillations were measured, then the two velocity components could be determined.

To be able to measure these two frequencies, it was necessary that they vary in two non-overlapping frequency bands. The glass discs supporting the gratings were rotated at two different velocities corresponding to two grating base frequencies $f_{Gz} = 1 \text{ MHz}$, and $f_{Gy} = 0.6 \text{ MHz}$. Figure 2.20 presents the actual frequency bands used during the experiments. The lower frequency band was chosen for the lateral velocity, since this component can have positive and negative values around the zero velocity. The separation of the two bands from the original velocity signal was obtained by using band-passed filtering. The band limits of the filtering as in Figure 2.20 were chosen to accomodate to the possible physical values of the velocity components.

2.2.5 Experimental Errors

The analysis of possible errors involved in the use of the present laser technique was made by Semiat and Dukler (1981) in general terms. Here, the analysis for the particular set-up of the present experiments will be made.

Figure 2.19

Ronchi Gratings orientation for two orthogonal component velocity measurements.

A possible cause of error is the problem involved with the droplet passage through the measuring volume along a particle chord and not along its diameter. From the Semiat and Dukler (1981) analysis, for the particular case of a slit of $75\text{ }\mu\text{m}$ and a measuring volume at a distance of $7500\text{ }\mu\text{m}$ from the slit, the resulting error for droplets in air was predicted to be almost zero. This is due to the fact that, with the particular configuration used, only droplets crossing the measuring volume along a particle diameter have any chance of being detected by the photodetector, PM2.

Another possible reason for experimental error is the presence of more than one particle inside the measuring volume. But from the analysis of the optical model developed in the previous section it was clear that in this case, two characteristic aspects will be present in the signals that will enable the detection of such a situation. The two aspects are:

- The passage time will lose its symmetric characteristic for a single spherical droplet. Even in these cases it is possible to obtain passage time values for the first and last particle which crossed the measuring volume. These passage time values are based on the first and the last particle half signals as already discussed. For intermediate particle signals no information can be obtained.
- The velocity signal generated in this case will have more than two frequency components which will make the frequency detection impossible and will prevent the possibility of a successful measurement of velocities. Only in the extreme cases of the first and the last particle of a multiple signal, while alone in the measuring volume, is it possible to detect unambiguous frequency information.

Figure 2.20
Experimental frequency bands used for axial and lateral velocity measurements.

The other possible reasons for experimental errors are related to diffraction phenomena. These phenomena result from the wave nature of the laser light. In the case of images created with closely spaced fringes these aspects must be analyzed. In the description used in previous sections for the image created by the laser crossing a Ronchi grating, the resulting diffraction patterns, or so called Fresnel images, were neglected. Actually, it is possible at certain distances from the Ronchi grating to create images that have a spatial frequency differing from the original fringe spacing, s_F . The spacial region where this is possible, according to Semiat and Dukler (1981), is confined to a distance equivalent to the region between zero and unity of the S parameter, defined as:

$$S = \frac{2s_F^2}{\lambda_{He-Ne}}, \quad (2.25)$$

where λ_{He-Ne} is the laser beam wavelength.

For $S = 1$, the distance is 7.9 mm, which is less than the actual distance of 50 mm from the measuring volume center to the Ronchi grating in the experimental set-up.

In the light pattern resulting from the crossing of a Ronchi grating by a laser beam, more than a single beam is generated, aligned along the direction normal to the fringe orientation and with decreasing intensities from the laser axis. This is the Fraunhofer diffraction pattern. The only resulting beam of interest for this technique is the one coincident with the laser axis. To eliminate the presence of the other beams, a circular slit of 1200 μm was placed at the top end of the quartz rod, through which the beam was introduced into the column.

Tests were made for drop size and velocity determinations, with glass beads of known diameters, d , at fixed known velocities v_z using the same spatial con-

figuration and optical equipment as in the experimental set-up. In the velocities measured the errors observed were less than 1%, which is the precision of the measuring instruments used. The maximum deviation on the diameter observed was independent of the particle size and had a positive value of $50\ \mu m$. This corresponds to a insignificant relative error for the largest particles but a considerable one for the smaller particle detected. This constant positive deviation could only be explained by the influence of the diffraction patterns on the smaller scales, since the errors involved with the velocity measurements and slit size measurement necessary to obtain the particle size through Equation 2.1, cannot explain such differences for the smaller particles. Since a way of obviating this problem was not found, the particle size measurements had to be taken with a precision of a $\pm 50\ \mu m$ maximum deviation, which is a considerable accuracy when considering the size ranges to be measured from $100\ \mu m$ to $3000\ \mu m$.

2.2.6 Signal Generation and Detection Equipment

The laser beam used was obtained from a Spectra-Physics Model 124-A $15\ mW$ He-Ne Laser. The laser was installed over a bench equipped with a system of three-dimensional micrometric displacements to allow for very precise alignment of the laser beam relative to the column test section (see Figure 2.21).

Over the same bench was also mounted the supporting system of the two Ronchi gratings. Figure 2.22 shows a schematic diagram of such a system. It consisted of two 4096 Line Count Discs of $74\ mm$ diameter with the fringe area contained in the concentric circular region between the $72\ mm$ and $58\ mm$ diameter values. The two discs were mounted on the shafts of two variable high speed motors. The

(A)

(B)

Figure 2.21

Photograph of laser set-up in test section and grating glass discs.

Figure 2.22
Schematic set-up of grating discs and driving motors.

motors were mounted on a vertical board in such a way that the fringes of the two gratings were oriented in orthogonal directions at the point where the laser had to cross the two discs. Figure 2.21-b shows the relative position of laser, gratings and column test section. A photocell directed toward the motor shaft used to monitor the rotation speed of the spinning motor can also be found.

The test section used for measurements was provided with several locations where the laser beam could be introduced inside the column through a 3 mm diameter quartz rod, to allow for the acquisition of data at different radial positions. A schematic representation of the three different equally spaced positions at 5 mm intervals from the center is shown in Figure 2.23. The position closest to the wall, $r_M = 2.0\text{ cm}$, could only be used for the lowest liquid rates. For higher liquid rates the liquid film bridged the quartz rod and the opposing optic fibers, preventing data taking at large liquid rates at this radial position.

The light passing through the 75 μm horizontal slit placed in front of the laser beam and the 1200 μm circular slit in the same vertical plane containing the laser beam, but now at a 38° angle with the laser, were both transported by means of optical fibers to the light intensity measuring devices. These were a RCA-7265 photomultiplier tube for the passage time signal and an RCA-8654 photomultiplier for the velocity signal. Both devices had a fast frequency response and were very sensitive, being capable of detecting signals of very high frequency. From both photomultipliers, PM1 and PM2, two analog voltage signals were obtained, which were subjected to some intermediate analog conditioning and final digital processing.

Figure 2.23

Cross sectional view of column test section radial distribution of experimental measuring locations.

2.3 Data Acquisition System

2.3.1 Analog Signal Conditioning

Figure 2.24 is a schematic diagram of the data acquisition system used for simultaneous measurements of two velocity components and size. The branches from PM1, the passage time signal, and PM2, the velocity signal up to the interface, are mostly concerned with the analog signal conditioning.

The passage time signal from PM1 was initially passed through a low-pass filter, set at 300 *KHz* cut-off frequency, to eliminate all the oscillating components of the signal related with the velocity signal. The smallest passage times measured were of the order of 10 μ s. After the filter, the signal was amplified to levels between the minimum and maximum voltages allowable by the analog-digital converter for the passage time signal.

The velocity signal from PM2 containing frequency information on the two velocities in two separate frequency bands was first passed through a band-pass filter, 300 *KHz* – 2 *MHz*, amplified, and then split into two signals, the radial velocity signal and the axial velocity signal. The radial signal was band-pass filtered, 500 *KHz* – 700 *KHz*, and then passed to a TSI Model 1990 frequency tracker. The axial velocity signal followed a parallel conditioning, but now band-pass filtered between 1 *MHz* to 2 *MHz*.

The frequency trackers detected the presence of a burst of light, due to a droplet crossing of the laser at the measuring volume, measured the frequency of the signal and transduced the measured frequency into a digital word with the frequency

DATA ACQUISITION SYSTEM

Figure 2.24

Data Acquisition System diagram for droplet size and two velocity components measurements.

information. A second analog signal from the tracker flagged the presence of a new digital frequency read-out whenever a velocity was detected. The frequency digital word and the detection flag signal from both trackers were connected to an interface for further digital processing.

2.3.2 Digital Processing of the Signals

The digital processing of the three signals was done by a specially designed interface. The inputs to the interface consisted of: an analog passage time signal, two digital flags from each tracker, and two digital frequency signals, one for each tracker.

The analog passage time signal was digitized at a rate of 500 *KHz*. At every 2 μs interval, a digital word of the passage time signal and one digital word from each frequency tracker was obtained. These 3-words were stored in a buffer memory, capable of storing 1024 sets of such words. The process of data storage was continuous until two analog signals from each tracker flagged a coincident velocity detection on the two trackers. After this event, only 512 additional data words were stored in the buffer memory and the analog-digital conversion stopped.

The data stored in memory contained 512 points before the velocity coincidence detection and 512 points after it. These data were then made available to a microcomputer, Apple II, where the digital signals were analyzed to extract passage time and velocity information. Once the data stored in the buffer memory was processed, the A/D conversion started again until a new coincidence was found. This process was repeated until a sufficient number of droplets were sampled for size, axial velocity and radial velocity measurements.

Figure 2.25 presents a photograph of the equipment involved in the signal conditioning and the digital processing as well as the microcomputer used. The left part of Figure 2.25-a shows the amplifier, filters and the oscilloscopes used to monitor the signals at different stages of the analog signal conditioning. On the right side, the two frequency trackers with the interface seated on the top, and the microcomputer can be found. Figure 2.25-b gives a perspective of the measuring test section in the vertical upflow loop where the data was actually taken.

2.3.3 Computer Signal Processing

The computer starts the analysis of the data once the A/D conversion is stopped and the interface buffer memory is filled with passage time and velocities information. This analysis is based on the passage time signal characteristics as discussed in Section 2.2.3.4. Computer programs were developed, which in the cases of either a single droplet detection or a droplet inside a multiple signal, extracted information on the passage time, τ_{PT} , axial velocity, v_z , radial velocity, v_y , and the droplet size, d . The result of such analysis for various cases can be found in Figure 2.26 in the form of a computer display graph. The inverted passage time signal is plotted *versus* the digital sample number, where the samples were at every $2 \mu s$ interval.

In Figure 2.26-a, a series of single droplets can be observed. Only one droplet crossed the laser beam through the measuring volume region. Two velocities were detected in this case, their values being displayed in the bottom of the picture ($v_z = 13.72 \text{ m/s}$, $v_y = -0.21 \text{ m/s}$), and the droplet size was computed ($d = 1657 \mu m$). Figure 2.26-b shows another single droplet detection, and in Figure 2.26-c is illustrated the case of a multiple droplet signal processed with successful acquisition of

(A)

(B)

Figure 2.25

Photograph of Data Acquisition System equipment and column Test Section.

data in one of the particles.

After the analysis of the signals data in the buffer memory, the droplet information was stored in the computer memory and the interface A/D conversion restarted again. The droplet data was transferred to a floppy disc unit and stored there for further statistical analysis. While in the data acquisition mode, the computer was always displaying the data obtained. After a specified number of droplets were measured, some statistics were computed to allow for a real-time control on the droplet sizes and velocities averages.

2.4 Data Statistical Analysis

For each experiment a sequence of N droplets was sampled, and for any particular droplet, information was obtained for droplet diameter, d_i , axial velocity, v_{zi} , and lateral velocity, v_{yi} , for $i = 1, \dots, N$.

A statistical analysis was performed for each measured variable according to the following procedure:

- The extreme values, minimum and maximum, of the measured samples were found.
- N_{CLASS} equal size class intervals of the variable between extreme values were formed. In each class interval, j , the number of droplets found there, N_j , was determined, for $j = 1, \dots, N_{CLASS}$.
- From this sequence, N_j , a probability density function, f , and probability distribution function was evaluated. This could be based either on the number distribution or volume distribution.

(A)

(B)

(C)

Figure 2.26

Computer graphic displays of typical Passage Time Signal traces and droplet size and velocities measurements.

- The statistical parameters of these distributions were then computed, namely, average values, median values, standard deviations, and second and third central moments.

This procedure was implemented by STAT4, a computer program presented in Appendix B.2. The results for all the experiments made can be found in Appendix A.2 for the droplet diameter, axial velocity, lateral velocity, absolute lateral velocity, and droplet angle.

One of the aspects under investigation was the possibility of finding correlations between the droplet sizes and the other measured variables. To this end, the following procedure was followed:

- The droplets sampled were sorted in an ascending order of particle size.
- Then they were categorized in N_{CLASS} classes of equal size range between the values of zero and the maximum droplet size observed in the experiment.
- In each class a statistical analysis was made, similar to the one described before, for all the measured variables.

This procedure was also implemented by program STAT4, and the results for all the experiments are presented in Appendix A.3. There, for each average class size, the average, median, and standard deviation values of the class can be found.

During the course of the next Chapters, several theoretical probability density functions will be proposed to fit the experimental density functions obtained. These theoretical distributions have a given number, N_P , of parameters. The parameter sets reported are the ones corresponding to the best fit found. They were chosen following a χ^2 *goodness-of-fit test* as proposed by Bendat and Piersol (1971). The

variable to optimize is an estimator of the χ^2 -parameter and defined as:

$$\chi^2 = \sum_{i=1}^{N_{CLASS}} \frac{(f_i^x - f_i^{x^*})^2}{f_i^{x^*}}, \quad (2.26)$$

where f_i^x represent the experimental values for the density function of the random variable x , and $f_i^{x^*}$ are the theoretical values predicted for a given set of parameters. The particular set of parameters that minimizes χ^2 was obtained by a finite difference, Levenberg-Marquardt optimization algorithm (Brown *et al.* 1971), implemented in a routine ZXSSQ of the IMSL computer software package. Once the minimum χ^2 value is found, then a level of significance of the parameters can be attributed by analysis of a χ^2 -Distribution Percentage Points table.

Chapter 3

Droplet Sizes in Annular Flow

3.1 Introduction

Under conditions of annular flow, as described in Chapter 1, the droplets moving with the gas core play a major role in the transport of heat, mass and momentum. The characteristic size of the droplets, or their distribution, is important to the understanding of these mechanisms. This chapter presents the results of measurements of droplet sizes and interprets the physical significance of the observed distributions.

In Section 3.2, the droplet size distributions are characterized. In Section 3.3 the effect of the flow rate on the distributions is explored, as well as their change with radial position. Section 3.4 analyzes the physical mechanisms that could possibly determine the observed distribution, and describes the controlling mechanisms that can be used to predict the size distributions observed.

To place this study in historical context, a review of earlier work is useful. Only studies on vertical upwards annular two-phase flow will be considered. There are two main groups based on the experimental technique used. A summary of all previous work can be found in Table 3.1.

The first group consists of studies based on measurement of droplet size through a photographic technique:

- Cousins and Hewitt (1968) performed experiments in a $9.5 \times 10^{-3} \text{ m}$ diameter column. They used two different superficial gas velocities, $U_{GS} = 29 \text{ m/s}$ and 50 m/s and collected between 260 and 1300 droplets per flow condition. A significant decrease of droplet size with increasing values of U_{GS} was observed, and this was independent of liquid rates.
- Pogson *et al.* (1970) made experiments in a heated $35 \times 10^{-3} \text{ m}$ diameter column. The small number of droplets measured per flow condition weakens the statistical reliability of the reported average sizes. Nevertheless, there is an apparent independence of droplet size with liquid rate.
- Ardon and Hall (1981) took data in a 161-rod, full-length heated rod bundle under a dispersed flow film boiling condition, where an annular pattern is observed. The equivalent diameter, D_e , of the flow rod cell was $20 \times 10^{-3} \text{ m}$. The experiments were run with vapor at $U_{GS} = 15 \text{ m/s}$ to 24 m/s , and data were taken at 2.7 m from the quench front. Owing to the insufficient number of flow conditions reported, no conclusions can be reached, except for the order of the magnitude of droplet sizes measured.

In the second group are included the studies based on indirect measurement of droplet size:

Table 3.1
Summary of previous measurements on drop sizes in vertical upwards annular flow.

Source	Geometry	Fluids	Tube Diameter (mm)	Experimental Technique	Gas Velocity Range (m/s)	Number of Flow Conditions	Number of Data Points per Flow Condition	Drop Size Reported	Droplet Size Range (μm)
Cousins & Hewitt (1968)	circular pipe	air/water	9.5	photographic	28.5-49.7	2 gas rates 3 liq. rates	258-1320	$\bar{d}_{32}$	48-87
Pogson <i>et al.</i> (1970)	circular pipe	steam/water	35	photographic	30	1 gas rate 5 liq. rates	max. 100	$\bar{d}_{32}$	34-56
Ardron & Hall (1981)	circular pipe	steam/water	15	video-tape	8-21	32	200-1200	$\bar{d}_{32}$	2000-10000
Tong <i>et al.</i> (1983)	rod bundle square pitch	steam/water	20*	cine-film	15-24	3	101-2034	$\bar{d}_{10}$	700-1200
Azzopardi <i>et al.</i> (1978)	circular pipe	air/water	30	laser diffraction	24-44	5 gas rates 5-11 liq. rates	—	$\bar{d}_{32}$	71-170
Ueda (1979)	circular pipe	air/water R113/glycerol	30 10	sampling oil slides	20-85	40	—	$\bar{d}_{20}$	15-80
Azzopardi <i>et al.</i> (1980)	circular pipe	air/water	32	laser diffraction	24-64	6 gas rates 3-8 liq. rates	—	$\bar{d}_{32}$	26-280
Azzopardi <i>et al.</i> (1983)	circular pipe	air/water	125	laser diffraction	28-40	3 gas rates 5 liq. rates	—	$\bar{d}_{32}$	60-125

* Equivalent diameter for a 4 rod flow cell

- Azzopardi *et al.* (1978,1980,1983) performed experiments in two different pipe diameters, $22 \times 10^{-3} \text{ m}$ and $125 \times 10^{-3} \text{ m}$ and varied the superficial gas velocity from 24 m/s to 64 m/s for the smaller tube and from 28 m/s to 64 m/s in the other. This used a laser diffraction technique, developed by Swithenbank (1976) and applied to annular two-phase flow for the first time by Azzopardi (1978). The main conclusions are a sharp dependence of mean droplet size on U_{GS} and a weak dependence on liquid flow rate. Also, with increased pipe diameter, an unexpected decrease in droplet size was found.
- Ueda (1979) performed experiments with two different pipe sizes, 30×10^{-3} and $10 \times 10^{-3} \text{ m}$, and varied U_{GS} in the range 20 m/s to 85 m/s . He used a technique based on direct impact of droplets on sampling oil slides. The same dependence on gas and liquid rates was found, although for the smaller pipe diameter, the droplet size decreased.

Besides these studies in vertical upward two-phase annular flow, there are many other measurements of droplet size for other flow patterns. Smith and Azzopardi (1978) summarized the experimental work on droplet size distributions in dispersed two-phase flow. It is important to mention the work done on vertical downward two-phase annular flow (Andreussi *et al.*, 1978); in downward channel flow (Wicks and Dukler, 1968); and in a horizontal pipe, (Tatterson *et al.*, 1977). From the analysis of previous studies, two conclusions can be drawn:

- i) The droplet size distribution is strongly dependent on gas flow rate, and the average size decreases as the gas flow rate increases.
- ii) The average droplet size is almost independent of the liquid rate.

These are important qualitative conclusions, but Table 3.1 reveals that there

is a wide disparity in the quantitative results obtained. This can have a twofold explanation: (a) either there is a preferred measurement of certain ranges of sizes, due to the experimental technique used; or (b) a statistical bias is imposed by the transient stochastic nature of the droplet size distribution, which imposes the need to average over a certain amount of time in order to obtain true time average statistical parameters.

With the exception of the work by Ardron and Hall (1981) and Tong *et al.* (1983), all studies used the technique of removal of the liquid film from the wall through a porous sinter. The region of droplet size measurement was always several diameters away from the film removal location. As will be shown later, the large droplets will tend to deposit in this short distance and the result will be biased towards the small droplets. Furthermore, the film removal system tends to create a radial flux of gas.

From all the experimental techniques used, those based on photographic data are certainly the most reliable. The ones using cine film or video cameras, have a lower limit around $200\ \mu m$ on droplet size detection. A bias for larger droplets is possible in these cases. With Ueda's (1979) technique of direct impact, the possibility of droplet shattering under impact with the oil slides is high. Rupe's (1950) study shows that for the droplet velocities characteristic of an annular flow pattern, the great majority of the droplets would shatter on impact with the sampling device. Therefore, a strong bias for smaller droplets is expected.

With the laser diffraction method used by Azzopardi, there are also two different sources of bias in the statistical results. The first is the non-uniformity of particle concentration in the measuring volume, and the second is the difference

in velocity observed for droplets of different sizes. According to Swithenbank *et al.* (1977), these are two possible reasons for errors in measurements. As will be shown in Chapter 4, the larger droplets travel faster than the smaller ones. This implies a shorter residence time of the larger particles in the measuring volume which will bias the statistics for the smaller sizes. Fernandes (1981) observed that under typical annular flow conditions, the column void fraction and related droplet concentration is not constant in time or even in space. The regions of high droplet concentrations are associated with the passage of roll waves, which usually have a low frequency of appearance in the measuring volume, but are responsible for most of the droplets entrained. In Azzopardi's works, none of these aspects are analyzed, and the instrument used was calibrated with stationary uniform particle suspensions.

The second major reason for the dispersion in reported data is the number of droplets sampled and how the droplets measured were sampled. The first aspect implies that a reasonable amount of samples has to be taken in order to increase the confidence levels on the computed statistics, as will be shown in Section 3.2. The second aspect refers to the problem involved with the amount of time necessary to obtain meaningful statistical parameters. At this point of annular flow understanding, generally all the equations used are time average equations. Therefore, the physical quantities to measure have also to be time averaged. In the presence of roll waves on the liquid film a typical time scale between two successive large waves can be of the order of 0.1–1.0 seconds. For instance, in the case of data obtained from photographic records, it usually corresponds to a few milliseconds of data averaging, since the exposure time per frame is of the order of tenths of milliseconds, and fewer

than 100 photos are analyzed per flow condition. With the use of cine or video films this problem can be resolved, but a considerable number of picture frames must be analyzed.

With the laser technique used in this work, all of these problems are circumvented. Sufficient droplets can be sampled in a reasonable time to give satisfactory statistical reliability. The sampling process takes place during a period of time long enough to obtain true time average statistics. The liquid film remains on the wall. The method can measure all droplet sizes greater than $75 \mu m$. droplets below this size carry a negligible amount of mass.

3.2 Droplet Size Characterization

The raw data resulting from each experiment, at a given radial position, r_M , and at fixed flow rates, U_{GS} and U_{LS} , is a sequence of droplet diameters, d_i , where i varies from 1 to N , where N is the total number of droplets sampled during the experiment. This sequence of N measurements of d_i is a sample of all dropletlets that pass through the measuring point. It is expected that this sample possesses the same statistical properties as the whole set of droplets.

d_i is a stochastic variable and is associated with a droplet size distribution. This distribution is fully characterized by a probability density function, f_d^N , for the droplets based on a number distribution, defined as :

$$f_d^N(\xi) = \frac{d}{d\xi} n(\xi), \quad 0 < \xi \leq d_{max}, \quad (3.1)$$

where $n(\xi)$ is the number fraction of droplets with diameter ξ , and f_d^N is subject

to:

$$\int_0^{d_{max}} f_d^N(\xi) d\xi = 1. \quad (3.2)$$

Once the function f_d^N is known, then all the statistical parameters of interest can be computed. In particular, a general form for the statistical mean diameter, $\bar{d}_{pq}$, as proposed by Mugele and Evans (1951) is:

$$(\bar{d}_{pq})^{p-q} = \frac{\int_0^{d_{max}} \xi^p f_d^N(\xi) d\xi}{\int_0^{d_{max}} \xi^q f_d^N(\xi) d\xi}. \quad (3.3)$$

For $q = 0$ and $p = 1, 2$ and 3 , the mean linear diameter, $\bar{d}_{10}$, the mean surface diameter $\bar{d}_{20}$, and the mean volume diameter $\bar{d}_{30}$ can be found. For $q = 2$ and $p = 3$, the Sauter mean diameter $\bar{d}_{32}$ is found. The particular values of p and q of interest depend on the subject under analysis. The relevant average for mass transfer, like adsorption on heterogeneous chemical reactions, where the surface area controls the transfer mechanisms, is $\bar{d}_{20}$. In the case of study of flow rate of droplets, for instance in hydrology or entrainment rates in annular flow, $\bar{d}_{30}$ is the useful mean. $\bar{d}_{10}$ is most suitable for comparison purposes, and $\bar{d}_{32}$ generally appears in computations of atomizing efficiencies (Mugele and Evans, 1951).

The diameter probability distribution function or diameter distribution function, F_d^N , on a number basis, is defined as:

$$F_d^N(d) = \int_0^d f_d^N(\xi) d\xi, \quad 0 < \xi < d_{max}, \quad (3.4)$$

and in particular, $F_d^N(d_{max}) = 1.0$. The value $F_d^N(d)$ expresses the fraction of droplets that have a droplet diameter smaller or equal to d .

From the experimental sequences of N droplets measured, since N is a finite number, a continuous distribution is not obtainable from experimental data. In

practice, a pointwise approximation is made to f_d^N . The method used, as described in Chapter 2, computes the values of f_d^N at a specific finite number of values of ξ , creating a discrete function $(f_d^N)_i$ for $i = 1, \dots, N_{CLASS}$, where N_{CLASS} is the total number of points or classes. The values of $(f_d^N)_i$ and respective $(F_d^N)_i$, for all flow conditions and radial positions, are listed in Appendix A.2, and were computed by means of the computer program STAT4, as described in Chapter 2.

Once the values of $(f_d^N)_i$ are computed, then all the necessary statistical parameters can be computed. In the case of mean diameters, defined through Equation 3.3, instead of continuous integral formulations, numerical quadrature of discrete functions have to be used. All the statistical parameters reported in Appendix A.2 were computed in this way.

The statistics of the droplet population can also be derived from the volume diameter density function f_d^V , which is defined by:

$$f_d^V(\xi) = \frac{d}{d\xi} V(\xi), \quad (3.5)$$

where $V(\xi)$ is the volume fraction of the drops with diameter ξ with:

$$\int_0^{d_{max}} f_d^V(\xi) d\xi = 1.0. \quad (3.6)$$

This function is related to the number based density function f_d^N , if the droplets are assumed all spherical, through:

$$f_d^V(d) = \frac{d^3 f_d^N(d)}{\int_0^{d_{max}} \xi^3 f_d^N(\xi) d\xi}. \quad (3.7)$$

Also a volume based diameter distribution, F_d^V , can be defined through:

$$F_d^V(d) = \int_0^d f_d^V(\xi) d\xi. \quad (3.8)$$

For this volume based distribution, a general form for statistical diameter means $\bar{d}_{pq}$, similar to Equation 3.3, can be obtained by replacing Equation 3.7 into Equation 3.3, resulting in:

$$(\bar{d}_{pq})^{p-q} = \frac{\int_0^{d_{max}} \xi^{p-3} f_d^V(\xi) d\xi}{\int_0^{d_{max}} \xi^{q-3} f_d^V(\xi) d\xi} . \quad (3.9)$$

The estimation of statistical parameters from volume distributions has been widely used in cases where particles are classified by size, after being measured on a volume basis for each size class. This is a useful technique in the cases where a high number of particles are collected and counting is cumbersome. For droplet systems this is seldom a problem and the number distributions are more useful. However, because some previous studies were based on volume distributions, their calculated values are presented in Appendix A.2.

The accuracy of the statistical values obtained for d depend on N . To assess how large the value of N should be, the following strategy was implemented:

- The values of $\bar{d}_{pq}$, for the specific cases of $\bar{d}_{10}$, $\bar{d}_{20}$, $\bar{d}_{30}$, and $\bar{d}_{32}$, were computed every time a new droplet was sampled. This creates discrete functions $\bar{d}_{10}(i)$, $\bar{d}_{20}(i)$, $\bar{d}_{30}(i)$, $\bar{d}_{32}(i)$, where i is the number of samples used to compute $\bar{d}_{pq}$.
- Once N samples were obtained, the following function $E_{pq}(i)$ was computed:

$$E_{pq}(i) = \frac{\bar{d}_{pq}(i)}{\bar{d}_{pq}(N)} , \quad i = 1, \dots, N . \quad (3.10)$$

In Figure 3.1, plots of these functions can be found for the extreme cases of gas and liquid rates in the domain of this work. As expected for small values of i , these functions present large oscillations around the value 1.0. For high values,

Figure 3.1
Evolution of the mean drop diameter with the number of droplets sampled.

$i > 400$, all the function values are contained inside a $\pm 5\%$ band, and the oscillation amplitude decreases as i increases. A value of i greater than 500 is enough to insure a maximum possible error of 5% , which is considered accurate enough for modelling proposes. Besides this test, the 95% confidence interval limits, e_{95}^d , were also computed for $\bar{d}_{10}$. These limits were computed for each experiment through the following relationship (Bendat and Piersol, 1971):

$$\bar{d}_{10} \pm \frac{s_{d_{10}} t_{N-1,0.025}}{\sqrt{N-1}} = \bar{d}_{10} \pm e_{95}^d, \quad (3.11)$$

where $s_{d_{10}}$ is the standard deviation of $\bar{d}_{10}$, defined according to:

$$s_{d_{10}} = \left[\int_0^{d_{max}} (\xi - \bar{d}_{10})^2 f_d^N(\xi) d\xi \right]^{1/2}, \quad (3.12)$$

and $t_{N-1,0.025}$, is the t-Student parameter, which for $N > 120$ and for 95% confidence limits, has the value of 1.98. The values of $\bar{d}_{10}$ and $s_{d_{10}}$ for all experiments can be found in Table 3.2. All these values show that the mean values of $\bar{d}_{10}$ are inside the region that deviates $\pm 5\%$ from the values obtained experimentally. In Figure 3.1, the confidence intervals of $\bar{d}_{10}$ are represented by dashed lines. These clearly show that all the average diameters reported will be within a $\pm 5\%$ error band.

The use of a functional form to represent the probability density functions obtained experimentally present several advantages. Namely, the drop size distributions can be represented entirely by a minimum set of parameters. This presents a substantial advantage compared with the long number listings required to express an experimental p.d.f., as in Appendix A.2.

Mugele and Evans (1951) analyzed the following expressions to represent the p.d.f. of droplet size in sprays: Rosin-Ramler, Nakiyama-Tanasawa, Log-Normal

Table 3.2

Summary of experimental values of the various mean drop diameters.

Exp #	U_{GS} (m/s)	U_{LS} (m/s)	r_M (cm)	N	$\bar{d}_{10} \pm e_{95}^d$ (μm)	$s_{d_{10}}$ (μm)	$\bar{d}_{20}$ (μm)	$\bar{d}_{30}$ (μm)	$\bar{d}_{32}$ (μm)	d^{95} (μm)	d^{99} (μm)	d_{max} (μm)
24	14.0	0.034	0.0	554	759 ± 38	453	848	950	1190	1562	1958	2475
23	15.9	0.034	0.0	577	731 ± 33	407	820	908	1114	1472	1818	2462
22	17.8	0.034	0.0	579	585 ± 26	316	664	735	904	1194	1433	2126
21	19.5	0.034	0.0	621	613 ± 25	324	676	746	909	1204	1456	1993
31	21.6	0.034	0.0	576	491 ± 20	250	539	592	715	950	1137	1596
26	24.7	0.034	0.0	676	423 ± 16	219	462	507	611	798	1028	1865
34	14.5	0.069	0.0	568	791 ± 31	378	882	964	1153	1538	1843	2296
33	17.5	0.069	0.0	573	647 ± 27	331	710	778	935	1244	1483	2136
30	21.5	0.069	0.0	588	469 ± 19	238	513	562	677	901	1071	1595
28	24.7	0.069	0.0	590	462 ± 18	226	512	561	673	889	1123	1663
25	14.1	0.121	0.0	563	763 ± 35	425	870	967	1195	1580	1915	2501
32	17.1	0.121	0.0	580	744 ± 31	383	823	902	1085	1442	1714	2487
29	21.5	0.121	0.0	585	636 ± 25	310	694	756	897	1195	1410	1863
27	24.5	0.121	0.0	585	550 ± 23	282	619	686	840	1088	1436	1983
40	24.6	0.034	2.0	577	590 ± 31	382	700	802	1053	1352	1691	2368
43	24.8	0.034	1.0	587	494 ± 18	221	529	569	658	878	1083	1868
26	24.7	0.034	0.0	676	423 ± 16	219	462	507	611	798	1028	1865
41	24.4	0.121	2.0	538	546 ± 29	340	646	738	964	1236	1566	2556
42	24.6	0.121	1.0	590	584 ± 23	288	645	706	846	1126	1350	2089
27	24.5	0.121	0.0	585	550 ± 23	282	619	686	840	1088	1436	1783
46	17.7	0.034	1.5	530	865 ± 42	490	1049	1185	1513	1969	2428	2353
44	17.7	0.034	1.0	577	676 ± 29	350	747	820	990	1312	1610	2365
22	17.8	0.034	0.0	579	585 ± 26	316	664	735	904	1194	1433	2126
47	17.5	0.121	1.5	522	914 ± 41	476	1016	1117	1348	1785	2124	2725
45	17.5	0.121	1.0	547	901 ± 35	417	995	1079	1267	1689	1979	2400
32	17.1	0.121	0.0	580	744 ± 31	383	823	902	1085	1442	1714	2487

and Upper-Limit Log-Normal (ULLN). Based on the data available, they found the ULLN equation to be the most convenient to use and proposed it as a standard to represent the drop distributions in sprays. Since then, most of the works concerned with p.d.f.'s of droplet sizes in annular dispersed flow have been testing this mathematical expression with relative success (Wicks, 1967; Tatterson *et al*, 1977; Andreussi *et al*, 1978; Ardron and Hall, 1981).

The ULLN density function is based on a normal distribution of a transformed variable η . The number normal density function is given by:

$$f_y^N(\eta) = \frac{\delta}{\sqrt{\pi}} \exp(-\delta^2 \eta^2), \quad -\infty < \eta < \infty, \quad (3.13)$$

where δ is a parameter and η is related to ξ by:

$$\eta = \ln \left(\frac{a\xi}{d_{max}^* - \xi} \right), \quad 0 < \xi < d_{max}^*, \quad (3.14)$$

where a and d_{max}^* are two additional parameters. To obtain the ULLN density function expressed in terms of droplet diameter, the use of a theorem of Statistics on a function of a random variable is needed (Davenport, 1970). Since the transformation of ξ on η is a one-to-one correspondence then:

$$f_y^N(\eta) = f_d^N(\xi) \left| \frac{d\xi}{d\eta} \right|. \quad (3.15)$$

From Equation (3.14):

$$\frac{d\eta}{d\xi} = \left(\frac{d_{max}^* - \xi}{d_{max}^*} \right). \quad (3.16)$$

Replacing (3.16) and (3.15) in (3.13) and rearranging, results in:

$$f_d^N(\xi) = \frac{\delta d_{max}^*}{\sqrt{\pi} \xi (d_{max}^* - \xi)} \exp \left[-\delta^2 \ln^2 \left(\frac{a\xi}{d_{max}^* - \xi} \right) \right], \quad 0 < \xi \leq d_{max}^*. \quad (3.17)$$

The ULLN distribution function can be derived from Equations 3.4 and 3.17:

$$\begin{aligned}
F_d^N(d) &= \int_0^d f_d^N(\xi) d\xi \\
&= \int_0^d \frac{\delta d_{max}^*}{\sqrt{\pi} \xi (d_{max}^* - \xi)} \exp \left[-\delta^2 \ln^2 \left(\frac{a\xi}{d_{max}^* - \xi} \right) \right] d\xi \\
&= \int_{-\infty}^y \frac{\delta}{\sqrt{\pi}} \exp(-\delta^2 \eta^2) dy = \frac{1}{2} [1 + \operatorname{erf}(\delta \eta)] .
\end{aligned} \tag{3.18}$$

The three parameters in the ULLN distribution can be related with meaningful diameter statistics. The parameter d_{max}^* characterizes the maximum expected diameter. The second parameter, a , is related to the median diameter, d^{50} , (the diameter below which 50% of the droplet population is contained) through:

$$a = \frac{d_{max} - d^{50}}{d^{50}} , \tag{3.19}$$

where this result can be obtained from Equation 3.18, by recalling that $\operatorname{erf}(0) = 0.0$. The third parameter, δ , can be expressed in several different ways. If d^{90} represents the value of d , for which $F_d^N(d) = 0.9$, then a possible expression for δ (Mugele and Evans, 1951), is:

$$\delta = 0.394 \left[\log \left(\frac{d^{90} d_{max}^* - d^{50}}{d^{50} d_{max}^* - d^{90}} \right) \right]^{-1} . \tag{3.20}$$

Hence, when d^{50} , d^{90} and d_{max} are obtained from the experimental p.d.f., a first set of parameters, d_{max}^* , a and δ can be computed. But their statistical reliability is not defined and depends on the reliability of d^{50} , d^{90} and d_{max} .

A different approach was followed in this work. As described in Chapter 2, whenever a p.d.f. was tested, a precise strategy of testing the goodness-of-fit was followed. This consisted in finding the values of d_{max}^* , a and δ that minimized the χ^2 -statistics. This quantity measures the goodness-of-fit between the proposed

Table 3.3

Summary of the parameters for the number and volume based drop diameter distribution functions.

Exp #	Number Distribution						Volume Distribution				
	d_{maz}^* (μm)	δ	a	χ^2	$\bar{d}_{10}$ (μm)		d_{maz}^* (μm)	δ	a	χ^2	$\bar{d}_{10}$ (μm)
24	2841	0.833	3.34	15.0	736		2475	0.512	0.43	147	64
23	2602	0.863	2.98	16.2	722		2832	0.806	1.01	91	470
22	2126	0.864	3.03	11.0	584		2166	0.832	1.01	67	363
21	2261	0.922	3.14	19.3	600		2276	0.844	1.02	42	430
31	1726	0.924	2.91	28.2	481		2018	0.877	1.28	59	335
26	2008	1.111	4.29	9.5	415		3377	0.974	3.30	62	280
34	2456	0.859	2.36	34.6	788		2296	0.836	0.77	59	563
33	2234	0.927	2.83	34.4	634		2712	0.858	1.27	98	428
30	1595	0.912	2.79	15.9	457		1958	0.879	1.36	43	308
28	1943	1.051	3.60	31.3	460		2331	0.868	1.59	241	301
25	2535	0.781	2.71	20.3	758		2917	0.797	1.08	69	433
32	2541	0.912	2.76	20.9	735		3028	0.860	1.19	129	513
29	2089	0.947	2.59	31.6	626		2505	0.949	1.35	58	477
27	2983	1.096	4.99	12.3	551		2812	1.009	1.86	68	445
40	2615	0.775	4.23	25.0	588		2368	0.629	0.805	89	157
43	1868	1.173	3.08	3.1	487		4430	1.253	4.531	67	427
41	2556	0.819	4.45	14.7	547		2556	0.710	1.240	57	201
42	2089	0.960	2.91	11.2	579		2316	0.927	1.350	60	421
46	3739	0.819	3.76	22.9	899		2631	0.723	0.573	92	547
44	2629	0.987	3.30	15.5	668		2984	0.945	1.504	77	508
47	2725	0.795	2.28	24.3	900		2787	0.786	0.761	34	576
45	2882	0.958	2.40	14.2	903		2676	1.014	0.903	30	835

χ^2 distribution values, $N_c = 20$, 3 parameters:

$$95\% \rightarrow \chi^2 = 30.2 ; 99\% \rightarrow \chi^2 = 35.7$$

theoretical expression for a p.d.f. and the experimentally measured discrete p.d.f. (Bendat and Piersol, 1971). The value of χ^2 obtained gives an objective measurement of the validity of the proposed ULLN density function as the p.d.f. of drop sizes in annular flow.

Table 3.3 presents the values of d_{max}^* , a and δ for all experiments based on the number distributions. The values of χ^2 are also given. Comparing the χ^2 values with a table of Percentage Points of χ^2 -Distribution (Table A.3 of Bendat and Piersol, 1971), it can be observed that in almost all cases the 5% level of significance of the goodness-of-fit test is verified, which means that the ULLN density function is a good representation of the experimental drop size distribution in annular flow.

It appears that an objective estimation of the fitting of the ULLN distribution has never before been made. The parameters reported in previous works were computed directly from the volume distribution function, F_d^V , and not from f_d^N , which are the direct results of experiments.

Besides the χ^2 values, the values of $\bar{d}_{10}$ computed with the ULLN distribution are also presented in Table 3.3. If the values of d_{max}^* and $\bar{d}_{10}$ are compared with the values found from the experimental p.d.f.'s, it can be concluded that:

- The values of $\bar{d}_{10}$ differ in the maximum in 3% and are always within the 95% confidence limits.
- The values of d_{max} and d_{max}^* in most cases are very close, except for two experiments. Excluding these cases, the deviations are all in the range of 0% to 20% .
- The values of a and δ found are all within a very close range.

The close proximity of d_{max} and d_{max}^* provides an extra piece of information.

There is no way of assessing the statistical reliability of the values of d_{max} measured experimentally. However, since d_{max} is close to d_{max}^* , it is then expected that the values of d_{max} found represent well the maximum possible diameter within a reasonable accuracy.

The ULLN distribution was also tested against the volume drop size distribution obtained experimentally. The expression for f_d^V is given by Equation 3.17, but the values of d_{max}^* , a and δ are different. The values found using the χ^2 strategy are also given in Table 3.3 as well as the values of $\bar{d}_{10}$ and χ^2 .

If the values of d_{max}^* and $\bar{d}_{10}$ obtained are compared with the ones in Table 3.1, the following conclusions can be drawn:

- The values of d_{max}^* found are not as close to d_{max} as the ones obtained from the number distributions.
- The values of $\bar{d}_{10}$ deviate from experimental values in the range of 10% to 90%, which is a very poor agreement.
- Most important, are the high values of χ^2 found, which indicate a poor fit.

This is a further indication that f_d^V should not be used in computation of drop size distributions.

In all the figures presented in the subsequent analysis, the plotted continuous representations of the density and distribution functions are the theoretical curves using the set of parameters given in Table 3.3.

3.3 Dependence of Drop Size Distribution on Flow Rates and Radial Position

A comparison of number and volume distribution clearly shows that, despite the fact that the smaller sizes dominate in numbers, the larger sizes carry most of the volume as mass. This can be seen from Figure 3.2 where the number and volume distribution are plotted for the four extreme conditions of liquid and gas rate combinations. For instance, in the case of $U_{GS} = 24.5 \text{ m/s}$ and $U_{LS} = 0.121 \text{ m/s}$, 50% of the drops below the mean diameter represented less than 10% of the volume, while 50% of the volume above the mean represented less than 10% of the drop count. As seen from the graphs of Figure 3.2, this describes the situation at all flow rates. This observation stresses the importance of the large drops in processes of momentum and mass transfer.

Table 3.2 contains drop size statistics for all flow rates and radial positions. It includes the gas and liquid volumetric fluxes, U_{GS} and U_{LS} , the most commonly reported mean drop sizes, $\bar{d}_{10}$, $\bar{d}_{20}$, $\bar{d}_{30}$ and $\bar{d}_{32}$, and also the maximum diameter d_{max} , as well as the d_{95} and d_{99} values.

The results show a strong dependence on U_{GS} . As the gas rate increases the drop size decreases continuously for all liquid rates, as is illustrated in Figures 3.3 and 3.4, for $\bar{d}_{10}$ and $\bar{d}_{32}$, respectively.

The dependence on liquid rates seems to be small. In the flow domain of the experiments U_{GS} is doubled, while U_{LS} is changed by a ratio of four. For the lowest gas rates, the average droplet diameters are almost equal, and a slight dependence on U_{LS} is observed for the larger values of U_{GS} .

When the values of d_{max} are plotted against U_{GS} in Figure 3.5, a strong

Figure 3.2
Number and volume based drop diameter distribution functions.

Figure 3.3
Dependence of the mean drop diameter, $\bar{d}_{10}$, on the flow rates.

Figure 3.4
Dependence of the mean drop diameter, $\bar{d}_{32}$, on the flow rates.

Figure 3.5
Dependence of the maximum detected drop diameter on the flow rates.

dependence on gas rates is found with a near independence on liquid rates.

The effect of U_{GS} and U_{LS} on the distribution of droplet sizes can be obtained from the study of the functions F_d^N and f_d^N . These functions are presented in Figures 3.6 and 3.7 respectively, where, for a fixed liquid rate, the curves at different values of U_{GS} are plotted. The evolution of the F_d^N curves with increasing U_{GS} can be explained by the depletion of the larger droplets from the total with an increase in number of smaller droplets. The fragmentation process intensifies as U_{GS} is increased. From the F_d^N curves, the influence of U_{LS} is not clearly perceptible.

It follows that the same reasons explain the behavior found in the f_d^N curves. But here the influence of U_{LS} is more evident. As U_{LS} increases, the peak values of f_d^N decrease. This, coupled with the fact that d_{max} is independent of U_{GS} , implies a larger uniformity on the droplet distribution. This tendency, with increasing values of U_{LS} , seems to be the only effect of the liquid rates on the droplet size distributions.

It is of interest to compare these results with the statistics on film thickness in vertical upwards annular flow, since all the droplets originated from the liquid film present on the walls of the pipe. In Figures 3.8 and 3.9, the results of Zabaras (1985) are presented for average film thickness, $\bar{m}$, and maximum film thickness, m_{max} . A dependence of these two variables on both gas and liquid rates was found. This contrasts with the independence of $\bar{d}_{10}$ and d_{max} on liquid rates, which is a clear indication that the mean drop sizes and d_{max} are mainly determined by the interactions of the droplets with the carrier gas, rather than the relation between a droplet and the liquid film from which it originated.

Table 3.2 presents drop size statistics for three radial positions, and for two

Figure 3.6

Dependence of the number drop diameter distribution function on the flow rates.

gas and two liquid rates. For the lower gas rate ($U_{GS} = 17 \text{ m/s}$), the position closest to the wall was $r_M = 1.5 \text{ cm}$, instead of the value $r_M = 2.0 \text{ cm}$ used for $U_{GS} = 24 \text{ m/s}$. This resulted from the inability to take data at lower gas rates at $r_M = 2.0 \text{ cm}$ due to the liquid film interference as is explained in Chapter 2.

Figure 3.10 presents the mean drop size, $\bar{d}_{10}$, profile for two gas rates and two different values of U_{LS} . There is some evidence that, as the droplets move towards the center of the column, the mean drop size decreases. This observation can have two possible explanations:

- The drops would have preferential directions for moving and the larger droplets would avoid the center region of the column, while the smaller ones would travel through the center. This is difficult to justify, since this would mean that the droplet trajectory in the radial direction would be controlled by the gas flow profiles. For this case, an inverted observation should have been made, since it would be precisely the smaller droplets that would avoid the center region of high gas velocities. Furthermore, it will be shown in Chapter 4, that the droplets trajectories are linear and determined by their own initial inertia, which exerts control over the whole size spectrum.
- The second possible reason is that droplets fragment or break-up as they move towards the center, because droplets passing there all have a flight time long enough for the break-up phenomena to take place.

This second explanation seems to be the only possible one, and is an additional confirmation that drop sizes are controlled by interactions with the gas curve. In Table 3.2, the values of d_{max} are also presented, and it is found that d_{max} has a maximum in the position close to the wall, and decreases for the positions closer

Figure 3.7
Dependence of the number drop diameter density function on the
gas flow rate.

to the center line. This implies that the larger droplets, after originating from the unstable liquid waves, progress into the gas phase and are subject to break-up before reaching the center position.

This progressive influence of the fragmentation process as the drop moves towards the center, is clearly observed on the F_d^N and f_d^N curves presented in Figures 3.11 and 3.12, respectively. Both figures show that the distribution functions shift to the smaller sizes toward the center line of the pipe.

The effect of increasing the liquid rate can be observed in these figures, to be that of making the droplet distributions more uniform. This observation provides important clues on the mechanisms controlling drop sizes in vertical upwards annular flow. It has been speculated so far that there are two possible types of mechanisms:

- A Kelvin-Helmholtz mechanism, where the droplet size is determined by the interaction of the gas phase with the liquid film, which would be unstable whenever there is present an unbalance between the restoring forces controlled by the surface tension, σ , and the suction forces created by Bernoulli effects due to gas flow across the top of the waves. The size of droplets would ultimately be determined by the break-up of the ligaments ejected into the gas phase. This mechanism was analyzed by James (1976), and an extension to annular flow was made using a linearized Kelvin-Helmoltz theory as suggested by Taylor (1950) and used by Bradley (1973) for a liquid film. Tatterson *et al.* (1977) used the same mechanism, but his final result was essentially an experimental correlation. In order for this mechanism to be the controlling one, it must be assumed that droplet break-up is not possible after drop formation.

Figure 3.8
Mean film thickness versus the superficial gas velocity. From Zabaras (1985).

- Interaction between the drops and the gas core causes droplet break-up. The source of the force controlling the break-up can have several origins. These will be analyzed in detail in Section 3.4.

Certainly both mechanisms play their role in the formation of drops, but it is important to ascertain which determines the drop size.

The facts that: (a) the average drop size decreases towards the center of the column; and (b) the weak dependence of the drop diameter on liquid rates; are a clear indication that the drop size is controlled by the mechanics of the gas droplet interaction. This mechanism will be analyzed in detail in next section.

3.4 Droplet Break-up Mechanisms.

The Critical Weber Number

The main objective of this section will be to identify the origin of the forces that control the drop size in annular vertical upwards two-phase flow. Photographic evidence shows that when roll waves are present on the liquid film droplets can form from these waves which can be larger than the maximum stable drop size. In this case they will break-up. The forces that resist to the droplet distortion acting on the gas-liquid interface can have two origins:

- The viscous forces developed by the internal movements of liquid inside the droplet. Hinze (1955), proposed that the importance of these forces, could be expressed by a dimensionless number, N_{ri} , defined as:

$$N_{ri} = \frac{\mu_l}{\sqrt{\rho_l \sigma d}}, \quad (3.21)$$

Figure 3.9
Maximum film thickness versus the superficial gas velocity. From Zabaras (1985).

Figure 3.10
Radial profiles for the mean drop diameter, $\bar{d}_{10}$.

Figure 3.11
Dependence of the number drop diameter distribution function
on the radial position.

where μ_l and ρ_l are the viscosity and density of the droplet, respectively, σ is the surface tension, and d is the droplet diameter. From his work, it was shown that, if $N_{ri} \ll 1$, then these forces have no significant effect on the break-up process. For the case of a large droplet in annular flow ($d = 10^{-3}m$, $\mu_l = 10^{-3}N.m/s^2$, $\rho_l = 10^3Kg/m^3$), $N_{ri} \approx 3.7 \times 10^{-3}$, indicating that viscous forces in the liquid droplet will play no significant role on the determination of the surface forces.

- The surface tension, σ , will create a surface stress, Δp_s , that is controlled by Laplace's law:

$$\Delta p_s = \frac{\sigma}{r_c}, \quad (3.22)$$

where r_c is the local radius of curvature. For the cases of liquid droplets in gas, this is the force that will oppose the external forces developed by the gas flow field around the droplets.

For the cases where the surface tension dominates, the maximum stable drop size will be determined by a balance between the external stress, τ , and the surface stress, Δp_s . These forces have to balance for a stable drop, i.e., they have to be of the same order of magnitude. Therefore the stability condition can be characterized by the ratio of these two stresses. This ratio defines a dimensionless number, the Weber number, We , defined as:

$$We = \frac{\tau}{\sigma/r_c} = \frac{\tau d}{2\sigma}. \quad (3.23)$$

The study of the value of We , above which the droplet is no longer stable, has been the subject of many investigations. This value is generally referred as the *critical Weber number*, We_c . In this case, d in Equation 3.23 should be replaced by d_{max} ,

Figure 3.12

Dependence of the number drop diameter density function on the radial position.

the maximum stable drop size:

$$We_c = \frac{\tau d_{max}}{2\sigma} . \quad (3.24)$$

In the Hinze (1955) paper, an analysis of what values to attribute to We_c , was made for different flow conditions. Following this work a series of studies appeared exploring the idea further. Of interest in the case of drops and bubbles in pipe flow are the works of Sleicher (1962), Sleicher (1965), Hughmark (1971), Sevik and Park (1973), and Kubie and Gardner (1977). In annular flow the works of Wicks and Dukler (1966), and Tatterson *et al.* (1977) should be considered. Basically these studies are concerned with the determination of We_c following the analysis of Hinze and comparing them with experimental data. Sevik and Park (1973) propose a theoretical determination of We_c as will be discussed below. Nonetheless, the subject is still open, and no final conclusions have been possible for the cases of droplets in annular flow. Therefore, the experimental data obtained from this study will be tested against the various possible controlling mechanisms, and from the results the applicable mechanism will be determined.

There are three possible sources for the force which can generate the external stress τ : the dynamic pressure forces; the gas shear; and the turbulent fluctuation of the pressure and velocity.

The force due to the dynamic pressure is developed through the flow of the gas around the droplet. Since the droplet and the gas are moving with different velocities a velocity distribution exists around the droplet. This creates a pressure distribution on the gas-droplet interface. Since the relative gas velocity is high, at least in the initial stages of droplet formation, the external shear will be mainly

determined by the pressure forces. In this case τ will be of the order of $\rho_g U_R^2$, where U_R is the relative gas velocity, and We_c will be given by:

$$We_c = \frac{\rho_g U_R^2}{2\sigma} d_{max} . \quad (3.25)$$

At the time of formation the drop is moving at a velocity close to that of the film. The film velocity is negligible compared to that of the gas during annular flow, and therefore $U_R \approx U_{GS}$. In this case:

$$We_c = \frac{\rho_g U_{GS}^2}{2\sigma} d_{max} . \quad (3.26)$$

In Figure 3.13, the values of We_c computed from experimental data are plotted against U_{GS} for different values of U_{LS} . A remarkably linear dependence of We_c on U_{GS} is found, rather than the constant value which would be expected if it were the dynamics pressures that controlled the drop stability. This increase of We_c with U_{GS} was also found in the Wicks and Dukler (1966) and Tatterson *et al.* (1977) data. Values of We_c calculated from Equation 3.26 in the range of 5 to 11, have also been observed by Lane (1951) and Hinze (1955) for a droplet in a transient blast of air and free fall in a steady air stream. The non-constant value of We_c suggests another mechanism is controlling.

The gas shear field is a source of stresses acting on the droplets. In liquid-liquid systems (Biesel and Acrivos (1973), Chin and Han (1980)), this can be an important mechanism for droplet break-up. The external stress term, τ , in Equation 3.24 can be estimated by choosing the maximum possible value for shear which corresponds to the interfacial stress τ_i . The new expression for We_c will be:

$$We_c = \frac{\tau_i d_{max}}{2\sigma} . \quad (3.37)$$

Figure 3.13
Critical Weber number *versus* the gas velocity

It will be shown in Chapter 5 that τ_i can be computed through the definition of an interfacial friction factor, f_i , as:

$$\tau_i = \frac{1}{2} \rho_g U_{GS}^2 f_i, \quad (3.28)$$

and f_i is related to Re_{GS} through:

$$\ln(f_i) = \frac{1.149 \times 10^{-5}}{Re_{GS}} - 5.491, \quad 4 \times 10^4 < Re_{GS} < 12 \times 10^4. \quad (3.29)$$

Therefore We_c can be computed through:

$$We_c = \frac{\tau_i}{2\sigma} d_{max} = \frac{f_i \rho_g U_{GS}^2}{4\sigma} d_{max}. \quad (3.30)$$

In Chapter 5, computations of f_i are presented for different values of U_{GS} , based on experimental data. For a droplet of $d_{max} = 10^{-3}m$, the maximum expected value of We_c is of the order of 5×10^{-2} . This value is too small if the gas shear field were controlling the droplet break-up. Hence, this mechanism is rejected as a possible controlling factor.

The third mechanism is based on the idea that the turbulent gas fluctuations acting over the drop create an average pressure fluctuation proportional to the product of the mean square velocity difference across an eddy, $\overline{v'^2}$, and the gas density, ρ_g . This average pressure fluctuation acting across a drop diameter causes distortion of the droplet and is the source of the stress term, τ . In order to estimate $\overline{v'^2}$, it is assumed that the maximum value of $\overline{v'^2}$ is that due to the eddies which are of the size of the maximum stable drop size. These eddies will present a mean square fluctuation velocity difference between two points, $\overline{v'^2}$, at a distance d_{max} , given by (Batchelor (1951)):

$$\overline{v'^2} = 2(P_M d_{max})^{2/3}, \quad (3.31)$$

where P_M is the energy dissipation rate per unit mass. Then the dynamic stress by the turbulent eddies around the droplet will be of the order of $\rho_g \overline{v'^2}$. Replacing this value for τ in Equation 3.24 gives:

$$We_c = \frac{\rho_g \overline{v'^2}}{2\sigma} d_{max} = \frac{\rho_g}{\sigma} P_M^{2/3} d_{max}^{5/3} . \quad (3.32)$$

The value of P_M will be obtained through:

$$P_M = \frac{U_{GS}}{\rho_g} \frac{dp}{dz} = \frac{U_{GS}}{\rho_g} \frac{4\tau_i}{D} = 2 f_i \frac{U_{GS}^3}{D} . \quad (3.33)$$

If experimental values of ρ_g , U_{GS} , f_i and d_{max} are obtained, and the values of $d_{max}^{5/3}$ are plotted against the group $\sigma \rho_g^{-1} P_M^{-2/3}$, then a straight line passing through the origin should be obtained where the slope is equal to We_c . Such a curve is plotted in Figure 3.14, using the experimental results of this work. A satisfactory dependence is found with $We_c = 0.194$, obtained from minimum least square fitting of the experimental points.

In annular flow, the energy dissipation is much higher than in single phase pipe flow. Hence f_i will be much larger. The use of single phase dissipation rates cannot give the right answer, and the drop sizes will be different in the absence of a liquid film.

It seems clear from this result that the turbulent field around the droplet controls the droplet size distribution in vertical upwards annular flow. This result is consistent with observations made by Hinze (1955) for the case of liquid droplets dispersed in a turbulent liquid, Sevik and Park (1973) for air bubbles entrained by a turbulent jet and even with the Sleicher (1962) experimental results for liquid droplets in turbulent liquid pipe flow as analyzed by Hughmark (1971).

Figure 3.14
Maximum diameter *versus* dissipation rate.

It is of interest to compare the value of We_c found in this study with the values found with other systems where the continuous phase is a turbulent fluid.

<u>Source</u>	<u>Fluid System</u>	<u>We_c</u>
Sevik and Park (1973)	Air bubbles in a water jet	1.3
Hinze (1955)	Liquid droplets in turbulent liquid of equal density	0.59
Present work	Water droplets in turbulent air stream	0.19

It is apparent that, when the viscosity ratio of dispersed phase to continuous phase increases, the values of We_c decreases. Sevik and Park (1973) were able to predict, theoretically, the value of $We_c = 1.24$ for the first case and $We_c = 0.52$ for the second case. Their derivations resulted from the following analysis.

In the theoretical study made by Lamb (1932) on oscillations of inviscid bubbles, the natural frequency of the n^{th} order mode of a spherical inviscid bubble undergoing small amplitude oscillations, was found to be:

$$(2\pi f_n)^2 = \frac{8n[(n+1)(n-1)(n+2)]\sigma}{[(n+1)\rho_d + n\rho_c]d^3}, \quad (3.34)$$

where the subscripts, d and c stand for dispersed and continuous phase respectively. For the case of gas bubbles in water, $\rho_d \gg \rho_c$ and Equation 3.34 will give for the first non-zero real value mode of oscillation:

$$f_2 = \left(\frac{24\sigma}{\pi^2 \rho_c d^3} \right)^{1/2}. \quad (3.35)$$

If the bubble is going to break-up, this can be achieved more likely whenever the energy is transferred from the continuous phase to the bubble at this natural frequency, since, in this case, the process of energy transfer and bubble oscillation will

be in phase. A characteristic frequency of the energy containing eddies, can be given by:

$$f = \frac{(\overline{v'^2})^{1/2}}{d} . \quad (3.36)$$

Therefore, whenever f_2 equals f , then an unstable drop of size d_{max} is found. This is equivalent to saying that:

$$\overline{v'^2} = (d_{max} f_2)^2 = \frac{24\sigma}{\pi^2 \rho_g d_{max}} , \quad (3.37)$$

replacing $\overline{v'^2}$ into Equation 3.32, results in:

$$We_c = \frac{\rho_c \overline{v'^2}}{2\sigma} d_{max} = \frac{12}{\pi^2} = 1.24 . \quad (3.38)$$

For the case of droplets in a turbulent liquid of equal density, a value of $We_c = 0.52$ is found in the same way.

For the case of the gas bubbles, the inviscid approach is probably valid. However, when the viscous nature of the oscillating droplet is of importance, the natural frequency modes cannot be obtained through Equation 3.34. Still, the fact that a good agreement for the case of gas bubbles was obtained is remarkable. It points out the correct mechanisms of energy transfer between the continuous and the dispersed phases. From annular flow visualization studies made by Whalley (1979), it was observed that the droplet break-up process can be described in the following way:

“Droplets emerge from a roll wave. The largest droplets with a diameter larger than the maximum stable size start oscillating for a while, and suddenly, irrespective of their position in the tube cross-section, a higher

frequency oscillation starts that results in the break-up of the droplet in a very short period."

This action possibly coincides with the tuning of the droplet oscillations to the turbulent oscillations of the eddies passing around the droplet. Hence, if this is the mechanism of transfer, an analysis of the characteristic frequency modes of oscillation of a viscous drop would predict the value of We_c . Until that analysis can be successfully made, the value of $We_c = 0.19$, as evaluated from this study with We_c defined as in Equation 3.32, is recommended.

An additional result of this analysis can be obtained when in the relationship expressed by Equation 3.32, the value of We_c is fixed. Then an expression for d_{max} is obtained:

$$d_{max} = \left(\frac{We_c \sigma}{\rho_g} \right)^{3/5} P_M^{-2/5}. \quad (3.39)$$

Furthermore, from the analysis of Table 3.3, a certain constancy in the ratios between d^{95} , d^{99} or d_{max} with any of the mean diameters, $\bar{d}_{pq}$, is observed. For instance, the ratio $d_{max}/\bar{d}_{32}$ has the value 2.3 ± 0.15 . Once this ratio is replaced in Equation 3.39, the following expression for $\bar{d}_{32}$ is obtained:

$$\begin{aligned} \bar{d}_{32} &= \frac{We_c^{3/5}}{2.3} \left(\frac{\sigma}{\rho_g} \right)^{3/5} P_M^{-2/5} \\ &= 0.49 \left(\frac{\sigma}{\rho_g} \right)^{3/5} P_M^{-2/5}. \end{aligned} \quad (3.40)$$

The values of $\bar{d}_{32}$ measured experimentally in this work and also in Cousins and Hewitt (1968), in a $9.5 \times 10^{-3} m$ diameter tube, are plotted in Figure 3.15 against the theoretical values obtained from Equation 3.40. It is observed that Equation 3.40 is able to predict correctly $\bar{d}_{32}$ within a 15% margin of error.

Figure 3.15
Theoretical and experimental values of the mean drop diameter,
 $\bar{d}_{32}$.

Chapter 4

Droplet Dynamics in Vertical Annular Flow

4.1 Introduction

The study of the dynamics of droplets in annular flow has been overlooked until recently despite the fact that, at flow conditions where the entrainment fraction is large, these droplets can largely control the transfer phenomena involved. The reason for this situation has been the lack of a suitable technique for simultaneous measurement of size and velocity of droplets.

Most earlier studies based their method of measurement of velocities and sizes on the analysis of photographic records obtained from high speed flash pictures of cine film or video tape. The main problem with these techniques is the considerable work involved in the processing of the photographic records. Therefore, it is no surprise that the photographic methods provide only a small number of measurements of size and velocity per flow condition. This implies a big uncertainty in the reported values of velocities and sizes.

Photographic techniques usually average the data over the optical space view. This means, in most cases, averaging over the tube cross section and over distances of several diameters in the axial direction. This averaging smooths out spatial distributions which could be present in the flow field. With the use of the technique presented here, a local measurement is possible.

As was pointed out in Chapter 2, with the laser technique it is possible to obtain simultaneous measurements of size and two components of the droplet velocity vector, $\underline{v}$, at a given location, namely, the local axial velocity, v_z , and the lateral velocity, v_y . In all reported photographic measurements, only a single velocity component was reported. In the following review of reported experimental data, a distinction between axial and radial velocities measurements will be made.

In the group concerned with axial velocity measurements, the following work has been reported:

- Cousins and Hewitt (1968) performed experiments in a $9.5 \times 10^{-3} \text{ m}$ diameter vertical column operated at two-phase vertical annular flow. They used two different superficial gas velocities, 28.5 and 49.7 m/s , and collected fewer than one hundred measurements per flow condition. They observed a slip velocity relative to U_{GS} that increased with increasing values of U_{GS} .
- Ardon and Hall (1981) made experiments in a heated $1.5 \times 10^{-2} \text{ m}$ diameter column with two-phase single-component vertical annular flow. They used video equipment coupled with strobe lights to record the movement of droplets at two different positions above the quench front formed at the bottom of the tube. They changed the superficial vapor velocities in the range between 5.5 to 13.4 m/s , values of U_{GS} which are very close to the flooding point. In their

case, flooding did not occur at these low values since the liquid film on the wall was being evaporated by the tube heated walls. The same increasing trend of slip velocity with gas velocity was observed.

- Tong *et al.* (1983) presented results obtained in a 161-rod, full-length heater rod bundle under a reflood dispersed flow, film boiling condition, where an annular flow pattern was observed above the quench front. The equivalent diameter, D_e , of the four rod cell was $2 \times 10^{-2} m$. The experiments were run at different vapor superficial velocities from 15 to 24 m/s and the measurements were taken at 2.7 m from the quench front. The same increase of slip velocity with U_{GS} was found, and, since the number of data points (around three hundred) per flow condition was high relative to the previous studies, a dependence between size and axial velocity of the droplets was observed similar to the one that will be presented later in this chapter.
- Yeoman *et al.* (1982) developed a two color crossed beam Laser Doppler Anemometry system for simultaneous measurement of droplet size and axial velocity and reported measurements in a $10^{-2} m$ diameter column at $U_{GS} = 47.5 m/s$. This doppler technique, based on the principles of Mie Scattering is valid only for drops smaller than $0.3 \times 10^{-4} m$. Since, as will be shown, much larger sizes exist in annular flow, this technique is not particularly useful. Nevertheless, for droplets of diameter around $3 \times 10^{-5} m$, there is still present a slip velocity of the order of 10 m/s for their experimental conditions.

The second group of measurements were concerned with the radial velocity.

- James *et al.* (1980) using a parallel light technique developed by Whalley *et al.* (1979) report radial velocity measurements at $U_{GS} = 24 m/s$ in a $2.2 \times 10^{-2} m$

diameter pipe. Following the trajectories of the droplets on a plane normal to the direction of the gas flow, they conclude that the radial velocity for particles greater than $2 \times 10^{-4} \text{ m}$, is mainly determined by the ejection velocity from the film on the wall, and remains constant during the time of droplet flight. The trajectories observed were almost linear and the average value of the radial velocity was of the order of 1 m/s .

- Andreussi and Azzopardi (1981) reanalyzed Whalley *et al.* (1979) work on cine films and reported measurements made at a new value of $U_{GS} = 55 \text{ m/s}$. A gas velocity effect on the average radial velocity of the droplets was detected. For the largest value of U_{GS} a higher value of radial velocities was found. No correlation between size and velocity was detected.
- Wilkes *et al.* (1983) using the same technique, now in a 10^{-2} m diameter column, reported data that show a dependence of the radial velocity on the column diameter. The values of the velocities detected were higher for the column of greater diameter.

A summary of all the work referenced above can be found in Table 4.1. It seems to be impossible to draw general conclusions from the previous work except that: (a) slip exists between droplets and gas; and (b) radial velocities are almost constant during a droplet's flight and are determined by the ejection velocity from the liquid film from where it was generated. Also, none of the previous studies made a systematic variation of the flow parameters, making it difficult to achieve any kind of quantitative conclusions.

In Section 4.2, an analysis of the experimental results of the two velocity components measured will be presented. The dependence of these velocities on flow

Table 4.1

Summary of previous experimental work on the simultaneous measurements of size and velocities of droplets in annular flow.

Source	Geometry	Fluids	Tube Diameter (mm)	Experimental Technique	Velocity Measured	Gas Velocity Range (m/s)	Number of Data Points per Flow Condition	Drop Size Range (μm)
Cousins & Hewitt (1968)	circular pipe	air/water	9.5	cine-film	Axial	28.5-49.7	max. 83	105-405
Ardron & Hall (1981)	circular pipe	steam/water	15	video-tape	Axial	5.5-13.4	max. 300	250-10000
Yeoman <i>et al</i> (1982)	circular pipe	air/water	10	two-color L.D.A.	Axial	47	max. 1000	max. 100
Tong <i>et al</i> (1983)	rod bundle square pitch	steam/water	20*	cine-film	Axial	15-24	max. 330	250-3000
James <i>et al</i> (1980)	circular pipe	air/water	22	parallel light	Radial	24	30	170-1150
Andreussi & Azzopardi (1981)	circular pipe	air/water	22	parallel light	Radial	24	min. 50	300-1000
Wilkes <i>et al</i> (1983)	circular pipe	air/water	10	parallel light	Radial	—	—	—

* Equivalent diameter for a 4 rod flow cell

conditions and droplet size will be studied. Trying to understand the physical mechanisms that control the behavior observed, a theoretical analysis of the dynamics of particles carried by a gas will be made in Section 4.3.

4.2 Experimental Data on Velocities of Droplets

4.2.1 The Stochastic Nature of the Velocity Vector of a Droplet

At any point M of the gas core of a column operating in an annular flow condition with coordinates (z_M, r_M, ϕ_M) a local cartesian frame of reference (x, y, z) can be assigned, and in particular, the point M can be the point where simultaneous measurements of velocity are taken. Any droplet which passes through M has associated with it a droplet diameter, d , and a velocity vector, $\underline{v}$. The velocity vector can be represented in terms of the local frame of reference, as:

$$\underline{v} = v_x \underline{i} + v_y \underline{j} + v_z \underline{k}, \quad (4.1)$$

where $\underline{i}$, $\underline{j}$, $\underline{k}$ are the unit directional vectors. With the experimental technique used in this work, two components of $\underline{v}$ can be measured:

v_z — the *axial velocity* in the direction of the flow;

v_y — the *lateral velocity* or *radial velocity* in the direction normal to the laser beam and normal to the axial direction.

Once a measurement is started, a sequence of droplets passes through point M . For any of the droplets measured, a set of the three measurements is taken.

This set forms a data vector, $\underline{D}_i$, where i is the droplet number, and the vector has components (d, v_y, v_z) . This vector behaves like a random vector, hence v_y and v_z are random variables themselves.

For each velocity, there is associated a probability density function f_{v_z} and f_{v_y} . Once these two functions are known, then any relevant statistical parameter can be computed. Therefore one of the objectives of the experimental measurements was to estimate such probability density functions.

To achieve such an objective, a sequence of experimental data vectors, (d_i, v_{yi}, v_{zi}) , for $i = 1, \dots, N$, where N is the total number of droplets analyzed, was obtained for each flow rate pair (U_{LS}, U_{GS}) . From these sequences, the p.d.f.'s can be estimated by using statistical methods as explained in Chapter 2. Once the p.d.f.'s were determined, the important statistical parameters were estimated from them.

To analyze the dependence of the statistical parameters on flow conditions, a systematic variation of flow rates was made and data taken at each flow condition. Another objective of this study was to find possible radial distributions of the velocities. This was achieved by making experiments at three radial positions.

For each one of the velocities under consideration the following analysis was performed:

- The average value and standard deviation of the p.d.f. were computed. Also the 95% confidence intervals were determined. This enables a comparison with the estimated experimental errors and gives an idea of the accuracy of the average values reported. The dependence of average values of velocities on flow rates is analyzed.

- A continuous functional form for the p.d.f. is proposed from the analysis of the discrete experimental p.d.f. The constants needed to specify the p.d.f. were computed as the set that minimizes the χ^2 -statistics, using the technique described in Chapter 2. The theoretical parameters of the p.d.f. are compared with the equivalent experimental values in order to assess the quality of the fit.
- From the experiments made at different radial positions, an analysis of the radial distribution of velocities was undertaken.
- An important aspect of this work is the ability to determine the effect of a particle size on its velocity. Sample sizes in this work were large enough so that conditional probabilities with good reliability could be calculated.

The result of this analysis for the axial velocity, v_z , and the lateral velocity, v_y , is presented in the next two sections.

4.2.2 Axial Velocity of Droplets in Annular Flow

A summary of the important statistical parameters obtained from the experimental data on axial velocities is presented in Table 4.2. Fourteen different flow conditions are reported at three different liquid flow rates with measurements taken at the center position ($r_M = 0$). Twelve experiments are reported at positions off the centerline. Additional information about flow conditions can be found in Table A.1 of Appendix A.

It is clear from the experimental results that there is a considerable dependence of the average axial velocity, $\bar{v}_z$, on the gas superficial velocity, U_{GS} . For all the liquid rates $\bar{v}_z$ increased with U_{GS} and was essentially independent of the liquid flow rate.

Table 4.2

Summary of experimental measurements of axial and slip velocities of droplets in annular flow.

Exp #	U_{GS} (m/s)	U_{LS} (m/s)	r_M (cm)	N	$\bar{v}_z \pm e_{95}^{v_z}$ (m/s)	s_{v_z} (m/s)	U_S (m/s)	S_R	$\bar{v}_z^*$ (m/s)	$s_{v_z}^*$ (m/s)	χ^2
24	14.0	0.034	0.0	554	11.8 ± 0.36	4.3	9.3	0.44	11.7	4.6	22.2
23	15.9	0.034	0.0	577	12.8 ± 0.34	4.1	10.4	0.45	12.8	4.3	12.7
22	17.8	0.034	0.0	579	13.4 ± 0.32	4.0	11.8	0.47	13.4	4.1	13.3
21	19.5	0.034	0.0	621	13.8 ± 0.32	4.1	12.9	0.48	13.8	4.2	12.4
31	21.6	0.034	0.0	576	14.3 ± 0.35	4.3	14.5	0.50	14.4	4.5	18.4
26	24.7	0.034	0.0	676	15.0 ± 0.33	4.4	17.2	0.53	15.0	4.5	12.2
34	14.5	0.069	0.0	568	14.0 ± 0.34	4.1	7.9	0.36	14.0	4.2	8.5
33	17.5	0.069	0.0	573	14.5 ± 0.35	4.3	10.1	0.41	14.5	4.3	15.5
30	21.5	0.069	0.0	588	14.5 ± 0.34	4.3	14.2	0.50	14.5	4.3	6.7
28	24.7	0.069	0.0	590	14.9 ± 0.36	4.4	17.3	0.54	14.9	4.6	8.3
25	14.1	0.121	0.0	563	12.5 ± 0.36	4.4	8.7	0.41	12.5	4.6	29.3
32	17.1	0.121	0.0	580	14.6 ± 0.37	4.6	9.5	0.39	14.6	4.6	6.9
29	21.5	0.121	0.0	585	15.2 ± 0.37	4.5	13.5	0.47	15.2	4.6	7.0
27	24.5	0.121	0.0	585	15.4 ± 0.37	4.6	16.5	0.52	15.5	4.9	21.6
40	24.6	0.034	2.0	577	12.3 ± 0.33	4.1	—	—	12.3	4.2	15.6
43	24.8	0.034	1.0	587	15.5 ± 0.35	4.3	—	—	15.4	4.5	14.1
26	24.7	0.034	0.0	676	15.0 ± 0.33	4.4	—	—	15.0	4.5	12.2
41	24.4	0.121	2.0	538	12.6 ± 0.32	3.8	—	—	12.5	3.7	3.0
42	24.6	0.121	1.0	590	14.2 ± 0.33	4.1	—	—	14.2	4.2	4.7
27	24.5	0.121	0.0	585	15.4 ± 0.37	4.6	—	—	15.5	4.9	8.3
46	17.7	0.034	1.5	530	11.5 ± 0.35	4.1	—	—	11.5	4.2	8.0
44	17.7	0.034	1.0	577	12.2 ± 0.33	4.0	—	—	12.2	4.1	9.2
22	17.8	0.034	0.0	579	13.2 ± 0.32	4.0	—	—	13.4	4.1	13.3
47	17.5	0.121	1.5	522	12.7 ± 0.37	4.3	—	—	12.8	4.5	16.7
45	17.5	0.121	1.0	547	13.2 ± 0.32	3.9	—	—	13.1	4.0	6.0
32	17.1	0.121	0.0	580	14.6 ± 0.37	4.6	—	—	14.6	4.6	6.9

χ^2 distribution values, $N_c = 20$, 2 parameters

95% $\rightarrow \chi^2 = 15.5$; 99% $\rightarrow \chi^2 = 22.0$

The definition of a slip velocity, U_S , is a convenient way of expressing the difference between the gas velocity and the droplet velocity. At the column axis ($r_M = 0$) a maximum gas velocity is present which can be estimated using the universal velocity profile for the gas core (Schlichting, 1979):

$$U_G|_{r_M=0} = 3.75u^* + U_{GS} , \quad (4.2)$$

where u^* is the gas friction velocity. This relationship is valid for rough pipes, thus independent of the wall conditions. The slip velocity for the center position can then be defined as :

$$U_S|_{r_M=0} = U_{GS} + 3.75u^* - \bar{v}_z(r_M = 0) . \quad (4.3)$$

The slip ratio S_R is defined as:

$$S_R = \frac{U_S}{U_G} , \quad (4.4-a)$$

which, at $r_M = 0$, will be given by:

$$S_R|_{r_M=0} = 1 - \frac{\bar{v}_z(r_M = 0) - 3.75u^*}{U_{GS}} . \quad (4.4-b)$$

Both values of U_S and S_R at the center position can be found in Table 4.2 using the values of friction velocities obtained in Chapter 5 and presented in Table 5.2. A plot of S_R against the gas Reynolds number, Re_{GS} , is shown in Figure 4.1 for different values of liquid rates. From this figure, it can be observed that S_R is an increasing function of Re_{GS} , and that the slip velocity increases faster than the local gas velocity. Also, there is almost no dependence of S_R on the flow liquid rates. This seems to indicate that the droplet velocity is mainly controlled by the

Figure 4.1

Experimental slip ratio versus gas Reynolds number at centerline.

gas flow rates. Since a relationship between S_R and Re_{GS} is needed in the next chapter, the following was obtained from the experimental results:

$$S_R|_{r_M=0} = 0.254 + 0.288 \times 10^{-5} Re_{GS} , \quad (4.5)$$

valid for $5 \times 10^4 < Re_{GS} < 10^5$. No general applicability of Equation 4.5 should be expected.

The standard deviation, s_{v_z} , of the axial drop velocity is almost independent of gas flow rate for a given liquid flow rate. This would be expected if the level of turbulence was constant with varying U_{GS} . It will be shown in Chapter 5 that the friction velocity, u^* , of the gas core is almost constant over the whole range of U_{GS} . Since the level of turbulence is proportional to u^* , as is found in single phase flow, the observed constancy of s_{v_z} should be expected. In Section 4.3 it will be shown that the turbulence intensity is a parameter of paramount importance in the determination of droplet velocities in a turbulent gas field.

From the analysis of the form of the experimental p.d.f. for the axial velocity, f_{v_z} , it seemed that this p.d.f. could be solely determined by two parameters: the average axial velocity, $\bar{v}_z$ and its standard deviation, s_{v_z} . Moreover, the form of this p.d.f. approaches that of a Gaussian distribution. This latter distribution has two parameters, $\bar{v}_z^*$ and $s_{v_z}^*$, and the theoretical p.d.f., $f_{v_z}^*$, is expressed by:

$$f_{v_z}^*(v_z) = \frac{1}{s_{v_z}^* \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{v_z - \bar{v}_z^*}{s_{v_z}^*} \right)^2 \right] . \quad (4.6)$$

From each experimental p.d.f., f_{v_z} , a theoretical $f_{v_z}^*$ was computed by choosing the values of $\bar{v}_z^*$ and $s_{v_z}^*$ that would minimize the χ^2 -statistics by the method explained in Chapter 2. The validity of $f_{v_z}^*$ to express the experimental f_{v_z} , can be tested

following a method suggested by Bendat and Piersol (1971) called the χ^2 *goodness-of-fit* criteria. The computed values of $\bar{v}_z^*$, $s_{v_z}^*$ and χ^2 can be found in Table 4.2. A very good agreement between the experimental values, $\bar{v}_z$ and s_{v_z} , and the theoretical values, $\bar{v}_z^*$ and $s_{v_z}^*$ was found. Furthermore, after consulting a Table of Percentage Points of the χ^2 distribution, it was observed that most of the fittings are better than the 5% level of acceptance. To test the results in a more explicit way, the plots of f_{v_z} and $f_{v_z}^*$ for the best and worst fit found, based on the values of the χ^2 in Table 4.2, are presented in Figures 4.2-a and 4.2-b. It seems that the Gaussian distribution does a reasonable job of representing the axial velocity distribution, f_{v_z} .

It seems suitable to use the Gaussian distribution as a model of f_{v_z} , although, it must be pointed out that this distribution predicts finite values of f_{v_z} for negative values of v_z . Nevertheless, these values are so small that for computational purposes they can be considered negligible. To avoid this problem, it can be postulated that $f_{v_z}^* = 0$ for $v_z \leq 0$ and a renormalization factor computed in order to satisfy the requirement that $\int_0^\infty f_{v_z}^* dv_z = 1.0$ by definition of p.d.f.

Once the Gaussian distribution is accepted, then an analysis of the influence of the flow parameters on f_{v_z} can be made. Plots of f_{v_z} for various values of U_{GS} and two different values of U_{LS} are shown in Figures 4.3-a and 4.3-b. From these plots it can be observed that as U_{GS} increases, f_{v_z} translates towards higher values of v_z . Also, increasing U_{LS} implies a spreading of the values of f_{v_z} reflected in the decrease of the maximum values of f_{v_z} from Figures 4.3-a to 4.3-b.

The next aspect to be analyzed is the spatial distribution of v_z . Experiments were performed at three different values of r_M . For each radial location, two dif-

Figure 4.2

Gaussian density function fit of experimental axial velocity p.d.f..
Best and worst fit at centerline.

ferent values of U_{GS} were used, and for each U_{GS} two different values of U_{LS} . For the lower value of U_{GS} , the closest possible location to the wall could not be achieved because of interference with the film as waves passed the measuring point. A summary of the important statistical parameters obtained from the experiments is presented in Table 4.3.

The average droplet velocity, $\bar{v}_z$ is plotted against r_M in Figure 4.4. These results reveal the presence of a velocity profile for $\bar{v}_z$, but, one that is only weakly dependent on r . The lowest values of $\bar{v}_z$ are found near the wall. Nevertheless, the curvature of the profile is very small for all cases and its shape seems to be maintained for different values of U_{GS} and U_{LS} .

The Gaussian distribution model for the p.d.f. of v_z again makes a reasonable fit for the experimental distributions at different radial positions (see Table 4.2). This extends the region of applicability of the Gaussian distribution for f_{v_z} to all cross sections of the gas core.

4.2.3 Lateral Velocity of Droplets in Annular Flow

Measurements of the lateral velocity, v_y , were performed simultaneously with the size and the axial velocity measurements already discussed. A summary of the statistics of the data obtained at all the radial positions is presented in Table 4.3.

As it can be observed from Table 4.3, the mean values of the lateral velocity, $\bar{v}_y$, are much smaller than mean axial velocities measured for the same conditions. This indicates the presence of small angles between the direction of the velocity vector of the particle and the column axis.

Figure 4.3
Dependence of droplet axial velocity p.d.f. on gas rates for different liquid rates.

An unambiguous estimation of the radial velocity can be obtained from the average value of the absolute lateral velocity, $\overline{|v_y|}$, which is a measure of how fast the droplets are moving radially. Values of $\overline{|v_y|}$ are found in Table 4.3 and plotted in Figure 4.5 *versus* the gas Reynold number, Re_{GS} , for all the radial positions. In this plot, for the experiments made at $r_M = 0$, it is observed that $\overline{|v_y|}$ is nearly constant in the whole range of Re_{GS} , with just a slight overall tendency to increase with Re_{GS} . In a first analysis this weak dependence of $\overline{|v_y|}$ on Re_{GS} is somewhat surprising, but, as was already mentioned and will be shown in Chapter 5, the friction velocity, u^* , is thought to be related to $\overline{|v_y|}$. In this study, the values of u^* are almost constant, ranging from 1.9 to 2.0 m/s.

Andreussi and Azzopardi (1981), following a suggestion made by Tatterson (1975), speculated that the kinetic energy of the droplet is proportional to the work done by the gas pressure forces on the wave just before droplet formation. The result is that the average droplet radial velocity should be proportional to the friction velocity, according to:

$$\overline{|v_y|} = \alpha \left(\frac{\rho_g}{\rho_l} \right)^{\frac{1}{2}} u^*, \quad (4.7)$$

where ρ_g and ρ_l are the gas and liquid phase densities, respectively, and α is a proportionality constant. Based on experimental data, a value of $\alpha = 12.0$ was suggested. In a more recent study, Wilkes *et al.* (1983) reported data on radial velocities of droplets in a pipe with a smaller diameter. They found a smaller value of α and concluded that there is probably a pipe diameter effect on $\overline{|v_y|}$. This nullifies the hypothesis for the mechanism proposed to be the one controlling the droplet radial velocity. But, in either case, for a fixed tube diameter a proportionality exists

Table 4.3

Summary of experimental measurements of lateral and radial velocities of droplets in annular flow.

Exp #	U_{GS} (m/s)	U_{LS} (m/s)	r_M (cm)	N	$\bar{v}_y \pm e_{95}^{v_y}$ (m/s)	s_{v_y} (m/s)	$\bar{v}_y^-$ (m/s)	$s_{v_y}^-$ (m/s)	χ^2	$ \bar{v}_y $ (m/s)	$s_{ v_y }$ (m/s)
24	14.0	0.034	0.0	554	0.30 ± 0.22	2.68	0.31	2.76	8.9	2.11	1.59
23	15.9	0.034	0.0	577	0.39 ± 0.24	2.90	0.40	3.05	13.8	2.29	1.76
22	17.8	0.034	0.0	579	0.27 ± 0.22	2.71	0.29	2.79	11.6	2.18	1.58
21	19.5	0.034	0.0	621	0.53 ± 0.23	2.88	0.57	3.03	10.6	2.37	1.68
31	21.6	0.034	0.0	576	-1.11 ± 0.26	3.15	-1.31	3.45	20.7	2.77	1.81
26	24.7	0.034	0.0	676	-0.61 ± 0.25	3.26	-0.71	3.66	27.0	2.73	1.88
34	14.5	0.069	0.0	568	-0.83 ± 0.27	3.25	-0.99	3.61	35.2	2.77	1.82
33	17.5	0.069	0.0	573	-0.91 ± 0.28	3.37	-1.19	3.83	35.5	2.92	1.85
30	21.5	0.069	0.0	588	-1.24 ± 0.25	3.07	-1.46	3.38	21.2	2.71	1.85
28	24.7	0.069	0.0	590	-1.70 ± 0.24	3.03	-2.10	3.04	16.5	2.90	1.88
25	14.1	0.121	0.0	563	0.41 ± 0.21	2.60	0.45	2.67	24.8	2.03	1.54
32	17.1	0.121	0.0	580	-0.84 ± 0.25	3.07	-1.01	3.38	26.1	2.61	1.76
29	21.5	0.121	0.0	585	-1.55 ± 0.26	3.26	-1.99	3.72	38.6	3.01	1.92
27	24.5	0.121	0.0	585	-1.51 ± 0.24	3.00	-1.84	3.37	38.6	2.75	1.84
40	24.6	0.034	2.0	577	-0.08 ± 0.23	2.77	-0.06	2.85	13.3	2.17	1.66
43	24.8	0.034	1.0	587	-1.27 ± 0.25	3.07	-1.50	3.32	10.0	2.69	1.84
26	24.7	0.034	0.0	676	-0.61 ± 0.25	3.26	-0.71	3.66	27.0	2.73	1.88
41	24.4	0.121	2.0	538	-0.31 ± 0.24	2.88	-0.34	3.00	7.0	2.28	1.71
42	24.6	0.121	1.0	590	-0.53 ± 0.26	3.21	-0.62	3.50	24.9	2.62	1.85
27	24.5	0.121	0.0	585	-1.51 ± 0.24	3.00	-1.84	3.37	38.6	2.75	1.84
46	17.7	0.034	1.5	530	0.26 ± 0.27	3.21	-0.30	3.43	17.0	2.58	1.86
44	17.7	0.034	1.0	577	-1.12 ± 0.20	2.49	-1.09	2.64	22.5	2.14	1.65
22	17.8	0.034	0.0	579	0.27 ± 0.22	2.71	0.29	2.79	11.6	2.18	1.58
47	17.5	0.121	1.5	522	-0.16 ± 0.29	3.43	-0.30	3.94	23.0	2.80	1.93
45	17.5	0.121	1.0	547	-0.87 ± 0.21	2.55	-0.85	2.66	42.7	2.13	1.62
32	17.1	0.121	0.0	580	-0.84 ± 0.25	3.07	-1.01	3.38	26.1	2.61	1.76

χ^2 distribution values, $N_c = 20$, 2 parameters

95% $\rightarrow \chi^2 = 15.5$; 99% $\rightarrow \chi^2 = 22.0$

between $\overline{|v_y|}$ and u^* . Then it is not surprising that the results in this study showed a value of $\overline{|v_y|}$ practically independent of Re_{GS} .

The experimental p.d.f., f_{v_y} , was also tested against the Gaussian distribution. Once again, the fit is reasonably good (see Table 4.3) but not as good as in the case of the axial velocity reflected in the larger values of χ^2 found.

From the measurements performed at different radial positions, f_{v_y} appears independent of the r_M . The values of $\overline{v_y}$ and $\overline{|v_y|}$ were within the same range as the ones obtained from the measurements at $r_M = 0$. This constancy of the average radial velocity along the column radius, suggests that the lateral velocity of the droplet is obtained in the process of droplet formation from the wavy liquid film at the wall and remains constant in its flight path.

From an analysis of the Whalley *et al.* (1979) movies, it would appear that the main mechanism of droplet formation in upwards annular flow is the undercutting of large disturbance waves by the gas phase. This mechanism can be described as follows:

- A large wave presents an obstruction to the fast moving gas. At the back of the wave a stagnation point is created and the impact pressure pressure undercuts the wave as shown in Figure 4.6.
- As the undercutting proceeds the pressure under the wave remains at the stagnation pressure, p_0 , which is higher than the pressure above the wave, p .
- The pressure difference, $(p_0 - p)$, is the driving force which tends to move the liquid outwards in all directions. There is obvious resistance in the axial direction due to the presence of liquid upstream. However in the radial direction no significant resistance can be found.

Figure 4.4

Average droplet axial velocity radial profiles for different flow rates

— The liquid is accelerated in the radial direction and eventually disperses.

A simple calculation can be made to assess the order of magnitude of the lateral velocities expected by this mechanism. Consider the undercut wave represented in Figure 4.6 with a liquid finger with a projected area, A_y , in the y -direction, and a thickness, ℓ_y . The driving force in the y -direction, F_y , can be estimated through:

$$F_y = (p_0 - p)A_y = \frac{1}{2}\rho_g U_{GS}^2 A_y, \quad (4.8)$$

where the wave velocity was neglected compared to gas velocity. This force has to equate to the rate of change of lateral momentum of the finger, i.e:

$$F_y = \frac{1}{2}\rho_g U_{GS}^2 A_y = \rho_L A_y \ell_y \frac{dv_y}{dt}, \quad (4.9)$$

with the finger volume approximated by the product $A_y \ell_y$. For a typical case of $\ell_y = 0.5 \text{ mm}$, $U_{GS} = 20 \text{ m/s}$, $\rho_g = 1.3 \text{ Kg/m}^3$, and $\rho_l = 10^3 \text{ Kg/m}^3$ a value for the lateral acceleration of $5.2 \times 10^2 \text{ m/s}^2$ is found. Assuming this acceleration to be maintained constant in the initial moments of the finger lateral movement, then for a finger displacement over a distance $4\ell_y$, a velocity $v_y = 2.0 \text{ m/s}$ is obtained which is in the range of the droplets lateral velocities measured in the experiments.

The real process is certainly more complicated, but, the forces predicted by the proposed mechanism can explain the correct order of magnitude of lateral velocities found. Therefore it is suggested the wave undercut mechanism determines the droplets lateral velocity.

4.2.4 Dependence of Droplet Velocities on their Sizes

The objective of the analysis in this section is to investigate the dependence of v_z and v_y on the particle size, d . In previous studies (Andreussi and Azzopardi,

Figure 4.5

Dependence of average radial velocity on flow rates and radial position

1981; Tong *et al.* , 1983), some idea of the velocity dependence on the diameter was deduced by plotting individual realizations of such measurements. Examples of such an approach appears in Figure 4.7 for the radial velocity (Andreussi and Azzopardi, 1981) and in Figure 4.8 for the axial velocity (Tong *et al.* , 1983). Because of the limited number of samples, the error associated with such plots is very high and only qualitative judgments can be drawn.

In this work, the large number of measurements at each flow condition permitted the use of conditional sampling analysis. From each experimental flow condition a set of N samples was obtained. For each droplet sampled, the size, d , and the velocities, v_z and v_y were measured. The droplets were then classified into classes of droplets of diameter, d^c . Classes were defined by dividing the interval $\{0 < d \leq d_{max}\}$, into fifteen equal sized intervals. The average class size, $\bar{d}^c$, and the average class velocities, $\bar{v}_z^c$ and $\bar{v}_y^c$, were computed for each one of these classes. These values and other relevant statistical parameters were calculated for all experimental conditions and are listed in Appendix A.3. In these tables the standard class deviation, $s_{v_z}^c$, and the number of drops in each class, N_c , can be found.

Figures 4.9-a through 4.9-c present the average droplet axial velocity as a function of the droplet diameter for $r_M = 0$ and three different values of U_{GS} . Data for $r_M \neq 0$ can be found in Figures 4.10-a through 4.10-d.

The startling, completely unexpected results which emerge from these data are that axial velocities increase markedly with increasing drop size. The larger droplets move faster than the smaller ones. In fact, the effect of the drop diameter is stronger than that of the gas velocity which provides the driving force. This is consistent for all liquid rates. For each class of size d^c , there is a distribution of

Figure 4.6

Wave undercut mechanism for droplet generation and radial velocity impact.

v_z with an average value $\bar{v}_z^c$ and a spread around $\bar{v}_z^c$. The values of the standard deviation, $s_{v_z}^c$, can be found in Table A.3, and are of the order of 3 m/s. Therefore, it is not necessarily true that a particle with larger value of d travels faster than particles with smaller diameter, but in average this is true for each class size and the trends found in the plots are statistical meaningful trends. As was shown in Chapter 3, the number of droplets in each class decreases for higher values of d^c . Only classes with at least ten samples are plotted to maintain reasonable statistical significance.

Droplets measured at center position ($r_M = 0$) should be driven by local gas velocities, U_G , that are on the order of $1.4U_{GS}$ according to Equation 4.2. Values of $\bar{v}_z^c$ higher than U_{GS} are expected and observed. The drops originate in the large waves. Over the waves the flow area for the gas is constricted resulting in a higher gas velocity. This provides a large initial driving force for the drop.

The results from measurements taken at different radial positions are plotted in Figure 4.10. It is observed that for given liquid and gas rates $\bar{v}_z^c$ increases towards the center. This is certainly due to the higher values of, U_G , as the centerline is approached. This is consistent with the velocity profile of $\bar{v}_z$ found previously.

It is interesting to observe that for the position closest to the wall, $r_M = 2.0 \text{ cm}$ (Figures 4.10-b and 4.10-d), the curve $\bar{v}_z^c$ versus $\bar{d}^c$ passes through a maximum, i.e., the large particles that are fastest at the center position are not necessarily the fastest closer to the wall. However, as they move towards the center, these large droplets undergo the biggest increase in velocity compared to the other sizes. This reveals that they are under the influence of larger accelerations than those of the smaller drops. This effect will be analyzed in the next section.

Figure 4.7

Droplet radial velocity *versus* droplet size. From Andreussi and Azzopardi (1981).

Figure 4.9
Experimental droplet axial velocity versus droplet size for different liquid rates and varying gas rates at centerline.

Other important conclusions can be drawn from the observed relationship between $\bar{v}_z^c$ and $\bar{d}^c$. The average droplet axial and slip velocities are increasing functions of the gas rate. As was shown in Section 4.2.2, the dependence of $\bar{v}_z$ on U_{GS} is rather weaker than expected, especially, since the drag depends on the square of the velocity difference. This can be explained by the shape of the $\bar{v}_z^c$ versus $\bar{d}^c$ curves. Figure 4.11 shows curves of $\bar{v}_z^c$ versus $\bar{d}^c$ for a given U_{LS} and two values of U_{GS} , along with probability density distributions of the drop sizes for each flow rate. An increase in the gas rate results in a shift to smaller drop sizes. The smaller drop sizes travel at lower velocities. Thus, the average velocity is lower than it would be if the size distribution remained unchanged when the gas rate increases.

The class averages of the lateral velocity, $\bar{v}_y^c$, and of the absolute lateral velocity, $|\bar{v}_y^c|$, were also computed, and are reported in Table A.3. The main observation from the analysis of these results is that there is an almost constant value of $\bar{v}_y^c$ and of $|\bar{v}_y^c|$ for all values of $\bar{d}^c$. This is in agreement with the results of Andreussi and Azzopardi (1981) who found no correlation between these variables. This observation reinforces the idea that the radial velocity of droplets in annular flow is mainly controlled by the velocity at which the droplets are ejected from the waves. This constancy of $\bar{v}_y^c$ and $|\bar{v}_y^c|$ also implies that the droplets have, in average, the same flight times, independent of their sizes. In the next section, the dynamics of droplets will be analyzed in a search for the mechanisms that control the observed v_z dependence on d .

Figure 4.10

Experimental droplet axial velocity *versus* droplet size for different gas and liquid rates and varying radial position.

4.3 Equation of Motion of a Particle Moving in a Fluid

Consider a particle, solid or liquid, of volume V and density ρ_p , at any arbitrary time, t , traveling in a fluid. The velocity vector relative to a fixed frame of reference is, $\underline{v}$, for the particle. There are two types of forces being exerted on the particle. The first type is the body force, $\underline{F}_B$. The second type is the force which originates from the interaction of the fluid with the particle and is called the surface force, $\underline{F}_S$. Applying Newton's second law to the particle, the following form for the equation of motion of the particle results:

$$\frac{d}{dt} (\rho_p V \underline{v}) = \underline{F}_S + \underline{F}_B . \quad (4.10)$$

If the particle density is taken to be constant,

$$\rho_p \frac{d}{dt} (V \underline{v}) = \underline{F}_S + \underline{F}_B , \quad (4.11)$$

and expanding the time derivative

$$V \frac{d\underline{v}}{dt} + \underline{v} \frac{dV}{dt} = \frac{1}{\rho_p} (\underline{F}_S + \underline{F}_B) . \quad (4.12)$$

If there is no mass transfer between the fluid and the particle, then $V = \text{constant}$. Replacing in Equation 4.10:

$$\frac{d\underline{v}}{dt} = \frac{1}{V \rho_p} (\underline{F}_S + \underline{F}_B) . \quad (4.13)$$

For the body force term, the only contribution that will be taken into consideration is the gravity force, therefore:

$$\underline{F}_B = -V \rho_p g \underline{k} , \quad (4.14)$$

Figure 4.11

Simultaneous droplet axial velocities and droplet size distributions for different liquid rates and varying gas rates.

Figure 4.11 continuation

Simultaneous droplet axial velocities and droplet size distributions for different liquid rates and varying gas rates.

where $\underline{k}$ is the unit vector pointed upwards in the vertical direction.

The surface force, $\underline{F}_S$, is the resultant of three distinct types of interactive forces:

- The skin drag force, $\underline{F}_{SD}$, due to the tangential forces developed on the surface as a result of velocity gradients. For newtonian fluids, which are always considered here, these stresses are determined by Stokes/Newton's law for a viscous fluid.
- The form drag force, $\underline{F}_{FD}$, which is a consequence of the pressure distribution around the sphere, which results from the velocity field around the particle. This term does not include the hydrostatic pressure gradient or the mean pressure gradient due to the flow of the gas in the conduit. In the case of a fluid particle, it also includes the contribution of the normal stresses at the interface. It is usual to couple these last two terms, $\underline{F}_{SD}$ and $\underline{F}_{FD}$, into a single force called the drag force:

$$\underline{F}_D = \underline{F}_{SD} + \underline{F}_{FD} . \quad (4.15)$$

- The buoyancy force, $\underline{F}_{BY}$, which results from the action of the hydrostatic pressure on the particle and the force due to any pressure gradient, $\underline{\nabla}p$, necessary to move the fluid in the conduit. A general form for the buoyancy force is:

$$\underline{F}_{BY} = V \rho_f g \underline{k} + \ell A_P \underline{\nabla}p , \quad (4.16)$$

where A_P is the projected area of the particle in a plane normal to $\underline{\nabla}p$, ℓ is the largest chord in the particle volume in the direction of $\underline{\nabla}p$, and ρ_f is the fluid density.

Finally, the total forces, $\underline{F}_S$, can be obtained through

$$\underline{F}_S = \underline{F}_{SD} + \underline{F}_{FD} + \underline{F}_{BY} . \quad (4.17)$$

Replacing Equations 4.14, 4.16 and 4.17 into Equation 4.13 and rearranging:

$$\frac{d\underline{v}}{dt} = \left(\frac{1-\gamma}{\gamma} \right) g\underline{k} + \frac{1}{V\rho_p} (\underline{F}_D - \ell A_P \underline{\nabla} p) , \quad (4.18)$$

where γ is the density ratio, ρ_p/ρ_f . It is important to observe, at this point, that the only assumptions made so far are: no mass transfer is present, and the only body force is gravity. No considerations about the nature or geometry of the particle were made and Equation 4.18 is of general application. At this point, some simplifications are necessary.

In this analysis the drops will be assumed to be spherical with volume V_{Sp} , with some considerations later as to the effect of shape. As already discussed, in annular flow nearly spherical shapes are observed. With this assumption, Equation 4.16 transforms into:

$$\frac{d\underline{v}}{dt} = \left(\frac{1-\gamma}{\gamma} \right) g\underline{k} - \frac{3}{2} \frac{1}{\rho_p} \underline{\nabla} p + \frac{1}{V_{Sp}\rho_p} \underline{F}_D . \quad (4.19)$$

Once γ , ρ_p , V_{Sp} and $\underline{\nabla} p$ are known, the only term left to determine is $\underline{F}_D$. To have a complete trace of the particle in the fluid, the position vector, $\underline{x}$, has to be known as a function of time. This can be achieved from the definition of $\underline{v}$,

$$\frac{d\underline{x}(t)}{dt} = \underline{v}(t) , \quad (4.20)$$

and integrating the system of differential equations given by 4.19 and 4.20.

But the term $\underline{F}_D$ in Equation 4.19 is not yet determined, and it is exactly this term that carries all the complicated aspects of determining the velocity dependence on time. The exact knowledge of $\underline{F}_D$ can only be obtained by using an

exact description of the velocity field of the continuous phase or experiments to determine $\underline{F}_D$. This problem has been the subject of much research which has been summarized in a recent book by Cliff *et al.* (1978).

An analysis of published studies on drag, reveals that most of the research has been directed towards analysis and measurements under conditions of steady motion in fields of low turbulence intensity. However, the effect of the dynamic behavior of the system or of the presence of high turbulence levels, as expected to exist here, is only beginning to be understood. Because it is so important to this work, a brief review of the state of the art is now presented.

4.3.1 Drag Force on a Particle

The theoretical and experimental results of research on particle drag up to the present time have been mostly concerned with one-dimensional motion of the particle, i.e., fall and rise of particles in stagnant fluids and particle movement parallel to the fluid motion. Consequently, the analysis made in most of this section, will only consider one-dimensional motion. Only at the end of this section, will a generalization for three-dimensional motion be made.

The equation of motion for one dimensional motion in the vertical direction is given by the scalar component of Equation 4.19:

$$\frac{dv}{dt} = \left(\frac{1 - \gamma}{\gamma} \right) g - \frac{3}{2} \frac{1}{\rho_p} \nabla p + \frac{1}{V_{Sp} \rho_p} F_D . \quad (4.21)$$

A particular form of Equation 4.21 is obtained when the particle achieves dynamic equilibrium, i.e., when the forces are in balance, implying a constant velocity.

The velocity achieved at equilibrium is called terminal velocity, v_T . In this case, Equation 4.21 transforms into:

$$\frac{dv_T}{dt} = \left(\frac{1-\gamma}{\gamma} \right) g - \frac{3}{2} \frac{1}{\rho_p} \nabla p + \frac{1}{V_{Sp} \rho_p} F_{D_T} = 0, \quad (4.22)$$

or

$$F_{D_T} = V_{Sp} \rho_f (\gamma - 1) g + \frac{3}{2} V_{Sp} \nabla p, \quad (4.23)$$

where F_{D_T} is the drag experienced by the particle at terminal velocity. At this steady state condition, the value of F_{D_T} can be computed easily as long as ρ_f , V_{Sp} , γ and ∇p are known. At the same time, the value of v_T can be measured experimentally. If this is known, it is possible to devise a relationship between F_{D_T} and v_T :

$$F_{D_T} = f(v_T; \text{parameters}). \quad (4.24)$$

When Equation 4.24 is replaced in Equation 4.23, an equation is obtained that expresses v_T as a function of ρ_f , V_{Sp} , γ and ∇p which are easily measurable quantities.

The question now is, what form should the function f assume in Equation 4.24. F_{D_T} is a drag force, and, as was mentioned in Section 4.3, this force is equal to zero whenever the velocity of the particle relative to the fluid is zero. If a relative velocity, v_R , is defined by:

$$v_R = v - U_G, \quad (4.25)$$

which takes the value v_{R_T} when $v = v_T$, then F_{D_T} has to be a function of v_{R_T} in such a way that when $v_{R_T} = 0$, $F_{D_T} = 0$. The usual way of expressing this is through:

$$-F_{D_T} = \frac{1}{2} C_D \rho_f A_P |v_{R_T}| v_{R_T}, \quad (4.26)$$

where C_D is the drag coefficient. Due to the dynamic similarity of the flows, for which the values of C_D are computed experimentally, C_D is only a function of the particle Reynolds number, Re . The particle Reynolds number is defined as:

$$Re = \frac{|v_R|d}{\nu_f}, \quad (4.27)$$

where d is the diameter of the particle and ν_f is the kinematic viscosity of the fluid. For $v_R = v_{R_T}$ then $Re = Re_T$. As will be shown later, if dynamic similarity is not observed, then other parameters besides Re have to be correlated with C_D . The value of C_D can be found through an equation obtained by replacing Equation 4.26 in Equation 4.23, resulting, for the case of a sphere, in:

$$C_D = \left(\frac{4}{3}(\gamma - 1)g + \frac{2}{\rho_f} \nabla p \right) \frac{d}{v_{R_T}^2}, \quad (4.28)$$

and once the values in the right hand side are determined experimentally, then an experimental expression for C_D versus Re can be found.

There are also some analytical solutions that give $C_D(Re)$, the most important one being Stokes's law, for the motion of solid spheres in an unperturbed stationary viscous fluid at very low velocities ($Re \ll 1$):

$$C_D = C_{D_{St}} = \frac{24}{Re_T}, \quad (4.29)$$

There is also a series of important solutions (Oseen, 1910; Proudman and Pearson, 1957; Proudman, 1969) that give approximate values of C_D for Reynolds numbers up to 1. For $1 < Re < 100$, only numerical solutions are available (Masliyah, 1970).

The value of the drag force at terminal velocity, F_{D_T} , is the asymptotic value of F_D in Equation 4.21, when t goes to infinity. In the next paragraphs, a series of

analytical and experimental relationships for F_D under non-equilibrium conditions is discussed.

The first problem to be analyzed is the unsteady rectilinear motion of a solid spherical particle in a stagnant fluid at very low Re . In this case, the equation that controls the fluid flow around the particle is Stokes's equation of motion. The original solution of such a problem is attributed to Basset, Boussinesq and Oseen (B.B.O.). An interesting derivation can be found in Landau and Lifshitz (1959). The B.B.O. equation for the drag force is the following:

$$-F_D = 3\pi\mu_f v d + \frac{1}{2}\rho_f V_{Sp} \frac{dv}{dt} + \frac{3}{2}d^2(\pi\rho_f\mu_f)^{\frac{1}{2}} \int_{-\infty}^t \left(\frac{dv}{dt}\right)_{t=s} (t-s)^{-\frac{1}{2}} ds. \quad (4.30)$$

The first term in Equation 4.30 can be rearranged using Equation 4.29, to give:

$$-F_D = C_{Dst} \left(\frac{1}{2}\rho_f v^2\right) \frac{\pi d^2}{4} + \frac{1}{2}\rho_f V_{Sp} \frac{dv}{dt} + \frac{3}{2}d^2(\pi\rho_f\mu_f)^{\frac{1}{2}} \int_{-\infty}^t \left(\frac{dv}{dt}\right)_{t=s} (t-s)^{-\frac{1}{2}} ds. \quad (4.31)$$

It is now clear that the first term corresponds to the Stokes drag for steady motion evaluated at the instantaneous velocity, v . The second term, the *added mass term*, results from the fact that acceleration of the particle also causes an acceleration of the surrounding fluid. The last term includes the *Basset history* integral. It results from changes in the velocity distribution around the particle as a result of accelerations. The important result in Equation 4.31 is that, besides the Stokes drag term, the unsteady conditions give rise to two additional terms.

When the velocity of the gas, U_G , is non-zero, the drag F_D has to be expressed

in terms of v_R . In the case where U_G also varies with time, then:

$$\begin{aligned}
 -F_D = & C_{D_{st}} \left(\frac{1}{2} \rho_f |v_R| v_R \right) \frac{\pi d^2}{4} + \frac{1}{2} \rho_f V_{Sp} \frac{dv_R}{dt} \\
 & + \frac{3}{2} d^2 (\pi \rho_f \mu_f)^{\frac{1}{2}} \int_{-\infty}^t \left(\frac{dv_R}{dt} \right)_{t=s} (t-s)^{-\frac{1}{2}} ds - \rho_f V_{Sp} \frac{dU_G}{dt} ,
 \end{aligned} \tag{4.32}$$

The last term in Equation 4.32 represents the additional force necessary to accelerate the fluid, which would occupy the volume of the sphere if this were absent. Replacing Equation 4.32 into the equation of motion (Equation 4.21) results in an integro-differential equation that can be solved numerically. In the case where the fluid follows an oscillatory motion, Molerus (1964) and Hjelmfelt and Mockros (1967) have developed complete solutions. The gas velocity is represented by:

$$U_G = A \omega \cos(\omega t) , \tag{4.33}$$

where A is the amplitude of oscillations and ω its frequency. Then the particle velocity can be expressed as:

$$v = \eta A \omega \cos(\omega t + \beta) , \tag{4.34}$$

and the values of η and β can be found numerically. This result permits one to answer questions like: can a particle follow exactly the path of the fluid? Lumley (1957) looked into this problem and proposed that, for a particle to follow the fluid motion, it should have a relaxation time, given by the ratio $d^2(2\gamma + 1)/36\nu_f$, which is small compared with the period of oscillation, $1/\omega$, of the fluid. In other words:

$$\frac{1}{\omega} \gg d^2 \frac{(2\gamma + 1)}{36\nu_f} \iff \tau_D = \frac{4\nu_f}{d^2\omega} \gg \frac{(2\gamma + 1)}{9} , \tag{4.35}$$

where τ_D is the Stokes number, a dimensionless period.

Consider a droplet of diameter equal to $100 \mu m$ and moving in an air current ($\nu_f = 1.4 \times 10^{-5} m^2/s$, $\gamma = 770$, $p = 1 atm$), then $w \ll 32.7 rad/s = 5.2 Hz$. In annular flow, the majority of the mass is carried in drops greater than $100 \mu m$ in diameter as shown in Chapter 2. Since the gas motion is highly turbulent much higher frequencies of oscillations than $5.2 Hz$ are expected, and the droplets cannot follow the fluid motion. Observe that, if the droplets were following the fluid motion, the relative velocity, v_R , would be almost zero, implying creeping motion.

The B.B.O. equation was developed for conditions of creeping motion. However, it is clear that in the presence of considerable slip, these conditions cannot be met. Odar and Hamilton (1964) suggested this modification to the B.B.O. equation for cases of higher Reynolds number:

$$\begin{aligned} -F_D = C_D \left(\frac{1}{2} \rho_f v^2 \right) \frac{\pi d^2}{4} + \Delta_A \frac{1}{2} V \rho_f \frac{dv}{dt} \\ + \Delta_H \frac{3}{2} d^2 (\pi \rho_f \mu_f)^{\frac{1}{2}} \int_{-\infty}^t \left(\frac{dv}{dt} \right)_{t=s} (t-s)^{-\frac{1}{2}} ds . \end{aligned} \quad (4.36)$$

This equation is valid only for stagnant fluids. The coefficients Δ_A and Δ_H accounting for acceleration effects are always of order one and were correlated against an *acceleration modulus*, M_A , defined as:

$$M_A = \frac{d}{v_R^2} \frac{dv_R}{dt} = \frac{d}{v^2} \frac{dv}{dt} \bigg|_{U_G=0} , \quad (4.37)$$

giving the following empirical relationships:

$$\Delta_A = 2.1 - 0.132 \frac{M_A^2}{1 + 0.12 M_A^2} , \quad (4.38)$$

$$\Delta_H = 0.48 + 0.52 \frac{M_A}{1 + M_A^3} . \quad (4.39)$$

In Equation 4.36, the drag coefficient, C_D , is evaluated at the instantaneous velocity, v , using the *standard drag curve* which will be discussed later.

This expression for F_D has been proven experimentally to work well for a wide range of γ and Re_T values, but only when the particle starts with $v = 0$. In this case Equation 4.36 transforms itself into the B.B.O. Equation. According to Clift *et al.* (1978), for a particle released in a flowing fluid, ($U_G \neq 0$), equations 4.38 and 4.39 are no longer valid, since they were not based on data for such conditions.

Another extension of the B.B.O. equation was made by Tchen (1947) who applied it to small particles in a turbulent field. His results were later analyzed by Corrsin and Lumley (1956), and a correction was proposed. This solution is only an approximation for relative creeping motion of particles smaller than the shortest wave length present in the gas turbulent field. This is not true for the droplet size found in the experiments in annular flow as discussed above.

In view of the uncertainty in the values of the empirical correction factors, Δ_A and Δ_H , suggested by Odar and Hamilton, since these values have been shown to be near one and since the terms involving the drag coefficient dominate the solution, it is suggested that the bases for calculation of drop dynamics be Equation 4.32 modified by allowing the drag coefficient to be different from that for Stokes' flow. In this case, the following equation is applicable for linear motion:

$$-F_D = \frac{3}{4} C_D \frac{V_{Sp} \rho_f}{d} |v_R| v_R + \frac{1}{2} \rho_f V_{Sp} \frac{dv_R}{dt} + \frac{3}{2} d^2 (\pi \rho_f \mu_f)^{\frac{1}{2}} B(t) - \rho_f V_{Sp} \frac{dU_G}{dt}, \quad (4.40)$$

where $B(t)$ is the Basset integral, given by:

$$B(t) = \int_{-\infty}^t \left(\frac{dv}{dt} \right)_{t=s} (t-s)^{-\frac{1}{2}} ds. \quad (4.41)$$

Due to the high value of the density ratio ($\gamma \approx 770$ for air-water at atmospheric pressure), the time derivative terms are usually found to be negligible compared to other terms in Equation 4.40. Also, the Basset term can be neglected for the initial motion whenever v_R is high and far from the value of v_{R_T} . These simplifications are based in the results found when the equation of motion is integrated as it will be shown in section 4.3.4. But when the droplet velocity is close to v_{R_T} , the Basset term has to be taken into account.

If the time derivative terms and the Basset term are neglected, then Equation 4.40 can be simplified and extended to three-dimensional motion through the following expression:

$$-F_D = \frac{3}{4} C_D \frac{V_{Sp} \rho_F}{d} |\underline{v}_R| \underline{v}_R, \quad (4.42)$$

where C_D is computed at a Reynolds number Re with a velocity $|\underline{v}_R|$. The simplification that C_D be calculated at v_{R_i} , the i^{th} component of $\underline{v}_R$ can lead to significant error for $Re > 1$, although correct in Stokes flow (see Rudinger, 1974).

Replacing Equation 4.42 in the equation of motion (Equation 4.19), results in:

$$\frac{d\underline{v}}{dt} = \left(\frac{1-\gamma}{\gamma} \right) g \underline{k} - \frac{3}{2} \frac{1}{\rho_p} \nabla p - \frac{3}{4} \frac{C_D}{\gamma d} |\underline{v}_R| \underline{v}_R, \quad (4.43)$$

where $\underline{v}_R = \underline{v} - \underline{U}_G$.

In order to solve Equation 4.43 it still remains to determine suitable drag coefficients.

4.3.2 The Drag Coefficient Curves

The most widely used and known drag curve for spheres is the *Standard Drag Curve* as shown in Figure 4.12. This curve represents the best fit to experimental

Figure 4.12
The Standard Drag Curve. From Clift *et al* (1978).

data of C_D values obtained for the motion of a smooth solid non-rotating sphere, moving at terminal relative velocity through an undisturbed and unbounded fluid. From the analysis of such curve, it can be observed that there are three distinct patterns of dependence of C_D on Re .

In the first region, $1 < Re < 10^3$, C_D is a decreasing function of Re . For $Re \ll 1$, the curve coincides asymptotically with Stokes's law. The evolution of the flow field around the sphere, as Re is increased from 0 to 10^3 can be viewed in the following way. In the region, $0 < Re < 20$, the viscous terms control the forces acting on the sphere. There exists a laminar boundary layer all around the sphere that decreases in thickness as the Re is increased. At $Re = 20$, separation of the boundary layer occurs. A steady recirculation wake is formed that widens and lengthens as Re is increased up to 130. After $Re = 20$, the form drag starts increasing in importance relative to the skin friction, as the separation point moves towards the front of the sphere. At $Re = 130$, the wake is no longer stable and vortex shedding starts. The drag curve starts to level out. At $Re = 150$, the form drag equals the skin drag and exceeds it from that point on. For $Re > 400$, the vortices start shedding alternatively from either side of the sphere, and the wake changes its size as the Re is increased.

In the second region, for $10^3 < Re < 5 \times 10^5$ the C_D values are almost constant and equal to 0.44. This is called the Newton's law range. In this range, as the Re is increased the separation point continues to move forward until it achieves a minimum angle measured from the front of 83° .

The third region starts at $Re = Re_c = 3.5 \times 10^5$ where a sharp discontinuity is observed in the C_D versus Re curve. This critical condition is associated with

the transition from laminar to turbulent flow of the boundary layer attached to the sphere. As a consequence, its velocity profile is flatter in the local normal direction which implies an increase in average momentum flux per unit thickness of boundary layer. This increase in momentum flux allows the boundary layer to sustain itself attached to the sphere, for a longer distance in the presence of the adverse pressure gradient existing around the sphere. Therefore, the separation point moves abruptly backwards, changing in this way the form drag contribution which is the dominant one at these high values of Re . For $Re > Re_c$, the flow is designated as supercritical. The separation point moves towards the front of the sphere, and, consequently, the C_D values increase again.

The data presented earlier in this Chapter revealed that velocity increases with particle size. Calculated values of Re for the experiments show that $10 < Re < 10^3$. In this range, as shown in Figure 4.12, C_D decreases with Re . The application of equation 4.43 indicates that for this condition, for the same flight time the largest droplets will travel slower than the smaller ones, a result contrary to experiment. It seems evident that the drag curve which applies for the case of drops in the gas core must be significantly different from that shown in Figure 4.12. Three possible reasons can be offered: (a) the drops distort from the spherical shape on which the data for Figure 4.12 is based; (b) the drag coefficient for accelerating droplets differs from that for steady flows on which the *standard curve* is based; and (c) the turbulence level of the entraining fluid influences significantly the shape of the drag curves.

In general, for $d < 1000 \mu m$ the particles are observed to be spherical and for $d > 1000 \mu m$ the distortions are small. Therefore it seems reasonable to expect this

deformation effect not to be too large.

For the second reason, it has been shown that the standard drag curve can be applied when the appropriate equation of motion is used, and when the turbulence level is zero. But, as it will be shown later, the acceleration of drops affects the Re_c value at which takes place the transition of the boundary layer surrounding the drop from laminar to turbulent.

The third effect requires the carrying fluid to be turbulent. There have been only a few studies devoted to this subject. The main reason is the difficulty in characterizing the turbulent flow in the presence of the dispersed phase. Most of what is known at this point is reviewed by Clift and Gauvin (1971). The most drastic effect of the presence of any significant level of turbulence on the drag values is on the critical Reynolds number. A strong dependence of Re_c on the level of turbulence present in the fluid flow field is observed. The level of turbulence can be characterized by a relative turbulence intensity, I_R , defined as the ratio of the root mean square turbulent velocity, u_{rms} , to the relative velocity of the particle:

$$I_R = \frac{u_{rms}}{v_R} . \quad (4.44)$$

No single study measured C_D values over the full Reynolds number range for $I_R \neq 0$. Therefore it is necessary to construct a piecewise description of the $C_D - Re$ relationship. Figure 4.13 presents a typical drag curve for a non-zero fixed value of I_R . The description of C_D versus Re can be divided in four branches (BC , CV , VM , and MI) delineated by Re_c , Re_V , and Re_M . All of these values depend strongly on I_R .

Based on experiments by Dryden *et al.* (1937) with fixed spheres and Torobin and Gauvin (1961) with spheres entrained in a moving fluid, Clift and Gauvin

Figure 4.13

Schematic particle drag curve for a fixed level of turbulence.

(1970) suggested the following relationships:

$$\log_{10} Re_c = 5.477 - 15.8I_R \quad \text{for } I_R \leq 0.15 , \quad (4.45)$$

$$\log_{10} Re_c = 3.371 - 1.75I_R \quad \text{for } I_R > 0.15 . \quad (4.46)$$

Based on their own experimental work, Clift and Gauvin (1971), suggested:

$$\log_{10} Re_M = 6.878 - 23.2I_R \quad \text{for } I_R \leq 0.15 , \quad (4.47)$$

$$\log_{10} Re_M = 3.663 - 1.77I_R \quad \text{for } I_R > 0.15 , \quad (4.48)$$

and

$$Re_V = \left[Re_c^3 Re_M^{(0.45+20I_R)} \right]^{1/(3.45+20I_R)} . \quad (4.49)$$

The applicable drag equations (Uhlerr and Sinclair, 1970; Clift and Gauvin, 1971) for each branch are the following:

$$C_D = 162I_R^{1/3} Re^{-1} \quad \text{for } 0.05 \leq I_R \leq 0.5$$

and $10 < Re < 50$, (4.50)

$$C_D = 0.133(1 + 150Re^{-1})^{1.565} + 4I_R \quad \text{for } 0.07 \leq I_R \leq 0.5$$

and $50 < Re < 700$, (4.51)

$$C_D = 0.3(Re/Re_c)^{-3} \quad \text{for } 0.9Re_c \leq Re \leq Re_V , \quad (4.52)$$

$$C_D = 0.3(Re/Re_M)^{(0.45+20I_R)} \quad \text{for } Re_V \leq Re \leq Re_M , \quad (4.53)$$

$$C_D = 3990(\log_{10} Re)^{-6.1} - 4.47 \times 10^5 I_R^{-0.97} Re^{-1.8}$$

for $I_R \geq 0.07$ and $Re_M \leq Re \leq 3 \times 10^4$, (4.54)

and for values of I_R smaller than the values covered by the previous equations a drag equation proposed by Clift and Gauvin (1970), will be used:

$$C_D = \frac{24}{Re} (1 + 0.15Re^{0.687}) + \frac{0.42}{(1 + 4.25 \times 10^4 Re^{-1.16})} \quad \text{for } Re \leq 10^5. \quad (4.55)$$

Equation 4.51 was extended to the range of $Re > 700$ and $I_R < 0.2$ due the lack of experimental data in this range. Equation 4.52 in the Clift and Gauvin (1971) paper presents a coefficient of 0.03 instead 0.3 which clearly is. Equation 4.54 shows an anomalous behavior at Re close to Re_M and is discontinuous at $Re = Re_M$. The use of this set of empirical equations in the solution of the equation of motion (Equation 4.43), presented a special problem when such discontinuities exist. Because these equations are empirical fits to data, it was considered convenient and correct to make a slight adjust to Equation 4.54 to make it convenient to use. A correction factor C_C is introduced into Equation 4.54:

$$C_D = 3990(\log_{10} Re)^{-6.1} - 4.47 \times 10^5 (I_R + C_C)^{-0.97} Re^{-1.8}, \quad (4.54-a)$$

where

$$C_C = k_1 \exp(k_2 I_R + k_3 Re) I_R^{k_4}, \quad (4.54-b)$$

where the constants present the following values:

$$k_1 = 2.42 \quad ; \quad k_2 = -6.01 \times 10^{-3} \quad ; \quad k_3 = -8.92 \times 10^{-3} \quad ; \quad k_4 = -2.72 \times 10^{-1}.$$

Figure 4.14 shows the drag curves obtained in this way for different values of I_R .

The only parameter which determines the drag curve is this I_R . Since these values of C_D were measured under conditions of turbulent flow, two other parameters could be involved. The first is the ratio of the turbulence scale to the particle

Figure 4.14

The particle drag curves for different levels of turbulence intensity.

diameter. Taylor (1936) suggested that the transition from a laminar to a turbulent boundary layer should be determined by the ratio of d by $\mathcal{L}$, where $\mathcal{L}$ is the Eulerian macroscale of turbulence. Torobin and Gauvin showed no such scale effects, so this parameter is not taken into account. The second is the acceleration modulus, M_A , defined by Equation 4.37. Torobin and Gauvin also observed no effect of M_A on the value of C_D . But Wang (1969) found that for higher values of M_A , the values of Re_c were shifted further to values even lower than the ones predicted by Equations 4.45 and 4.46. Unfortunately, these observations were not quantified, and the measured values of C_D , were all taken in the *transcritical zone*, i.e. the region after the maximum on the drag curve after Re_c (see Figure 4.13).

If the effects of acceleration are ignored, the drag curve generated by Equations 4.45 through 4.54 can be used in the equation of motion (Equation 4.43) to calculate the dynamic behavior of droplets in annular flow. The values of terminal velocities of droplets in annular flow are discussed in Section 4.3.3; and the dependence of velocity on particle size is treated in Section 4.3.4.

4.3.3 The Terminal Velocity of Droplets in Annular Flow

The terminal velocity for the droplet is achieved when the forces acting on it are in balance. This corresponds to setting $d\underline{v}/dt = 0$ in Equation 4.43. Then the terminal velocity, v_{R_T} , will be given by the solution of the following vectorial equation:

$$\left(\frac{1-\gamma}{\gamma}\right) g\underline{k} - \frac{3}{2} \frac{1}{\rho_p} \nabla p - \frac{3}{4} \frac{C_D}{\gamma d} |\underline{v}_{R_T}| \underline{v}_{R_T} = 0. \quad (4.56)$$

If the *drag curve* (Equations 4.45-4.54) is used in conjunction with Equation 4.56, an implicit equation for v_{R_T} is obtained. For the case where the pressure gradient

contribution is negligible, and for vertical rectilinear motion where v_R is the relative velocity, Equation 4.56 reduces to:

$$(\gamma - 1)g + \frac{3}{4} \frac{C_D}{d} |v_{R_T}| v_{R_T} = 0. \quad (4.57)$$

The solutions of this equation, for the case of water droplets in air at atmospheric pressure, are plotted in Figure 4.15 where the standard drag curve was used in the case of $I_R = 0$. This reveals that, if the droplets are being entrained vertically by an air current, with $I_R = 0$, the smallest droplets will travel faster than the larger ones when equilibrium is achieved.

For $I_R \neq 0$, a systematic search for solutions of Equation 4.57 was performed. For every diameter increment of $50\mu m$ over the range $0 < d < 3000 \mu m$, the existence of solutions was determined numerically in each interval of terminal velocity of $0.1 m/s$ in the range of 0 to $30 m/s$.

In Figures 4.16 through 4.18 are plotted the solutions of Equation 4.57 in the form of $|v_{R_T}|$ versus d , for selected values of the turbulence intensity, u_{rms} . For certain values of d , and at fixed u_{rms} , there are multiple values of v_{R_T} that satisfy Equation 4.57. The number of solutions for a given d , or the multiplicity degree, is always an odd number, being 1, 3 or 5. Also, it is no longer always true that larger diameters correspond to higher terminal velocities. This depends on the particular values of d and u_{rms} .

Each point in Figures 4.15 through 4.18 is identified with the particular branch of the drag curve where the drag coefficient is found for that terminal velocity (see Figure 4.13).

The particular values of u_{rms} selected to be plotted represent typical cases of each type of the ten different bifurcation diagrams found. The evolution of these

Figure 4.15
 Terminal velocity dependence on droplet size for $u_{rms} = 0$.

Figure 4.16
Bifurcation diagrams of terminal velocity versus droplet size for
 $U_{rms} = 1.1, 1.2, \text{ and } 1.6 \text{ m/s}$.

diagrams with increasing values of u_{rms} , can be described as follows:

- $0.0 < u_{rms} \leq 0.9$, a single valued solution curve is found similar to the one found for $I_R = 0$ in Figure 4.15.
- $0.9 < u_{rms} \leq 1.1$, the first multi-valued region of the solution. In this particular case a single region of multiplicity three, forms a bifurcation diagram of the *hysteresis* type, Figure 4.16-a.
- $1.1 < u_{rms} \leq 1.5$, a second region of multiplicity three appears, of the same *hysteresis* type, for lower values of d , Figure 4.16-b.
- $1.5 < u_{rms} \leq 1.6$, the region of multiplicity three at higher values of d unfolds and a single multi-valued region is maintained, Figure 4.16-c.
- $1.6 < u_{rms} \leq 2.0$, a new multi-valued region of multiplicity three shows at larger values of d but now with a different appearance from the previous ones. This region consists on a top branch from the preceding diagram and underneath it a *finger* type branch, constituting an *isola* type bifurcation diagram. This *finger* moves upwards as u_{rms} increases and touches the top branch at $u_{rms} = 2$, Figure 4.17-a.
- $2.0 < u_{rms} \leq 2.3$, a new *finger* branch is created at the top region of the diagram with the same upwards trend with u_{rms} . The branch below the *finger*, folds on itself forming a new kind of bifurcation diagram of the *mushroom* type, and a region of multiplicity five appears for the first time, Figure 4.17-b.
- $2.3 < u_{rms} \leq 2.4$, the *finger* moves further to the top and right region of the diagram finally causing the region of multiplicity five to disappear, Figure 4.17-c.
- $2.4 < u_{rms} \leq 2.7$, three regions of multiplicity three can be found, Figure

Figure 4.17
Bifurcation diagrams of terminal velocity versus droplet size for
 $u_{rms} = 2.0, 2.3$, and 2.4 m/s .

4.18-a.

- $2.7 < u_{rms} \leq 2.9$, the folding of the lower branch for larger particles continues and two regions of multiplicity three are present, Figure 4.18-b.
- $2.9 < u_{rms} \leq 5$, a new region of multiplicity five can be found for the lower particle size range. Meanwhile, the top *finger* moved out of the diagram region, Figure 4.18-c.

The possible existence of multiple solutions raises the problem of stability of such solutions. This problem can be analyzed by recasting Equation 4.57 in terms of forces and by asking the question: when the forces balance, are they in a stable or in an unstable equilibrium?

If both sides of Equation 4.57 are multiplied by V_{Sp} then:

$$(1 - \gamma)gV_{Sp} = C_D \left(\frac{1}{2} \rho_f |v_{R_T}| v_{R_T} \right) \frac{\pi d^2}{4}, \quad (4.58)$$

which expresses the fact that in equilibrium, i.e. $v_R = v_{R_T}$, the gravity force F_G equals the drag force F_D . Therefore, in general, the ratio of these two forces can be expressed as:

$$\frac{F_D}{F_G} = \frac{C_D \left(\frac{1}{2} \rho_f |v_R| v_R \right) \pi d^2}{4(1 - \gamma)gV_{Sp}} = g_R(v_R), \quad (4.59)$$

where $g_R(v_R)$ is a function that takes the value one, whenever $v_R = v_{R_T}$. In Figure 4.19, this function is shown for $u_{rms} = 4.5$ m/s and for three different sizes. For the two lower values of d , the function $g_R(v_R)$ takes the value one for three different values of v_{R_T} and for the largest only once. Consider, for the sake of analysis, only the curve for $d = 750$ μm . There are three points, S_1 , U_2 , and

Figure 4.18
Bifurcation diagrams of terminal velocity versus droplet size for
 $u_{rms} = 2.6, 2.8, \text{ and } 3.0 \text{ m/s}$.

S_3 , where g_R takes the value one. The stability of each point can be inspected by analyzing the behavior of g_R around each one of this points.

Around the point S_1 , the behavior of g_R is as follows: if $|v_R|$ is increased, then g_R is greater than one, which means that the drag force is greater than the gravity force. Consequently v , the particle velocity, will increase, with a consequent decrease of $|v_R|$. Thus the droplet has the tendency to return to S_1 and the point is stable. If $|v_R|$ is decreased below V_{R_T} at S_1 , the drag force is smaller than the gravity force and the particle deaccelerates, v decreases, $|v_R|$ increases, and the condition retrieves to S_1 . This behavior is associated with the positive slope of g_R at S_1 . Since S_2 presents the same positive slope, S_1 behaves like S_2 , they both qualify as stable.

Around point U_2 the following is observed: if $|v_R|$ is increased, g_R is less than one, i.e., the gravity force is greater than the drag force, therefore the particle will accelerate, hence decreasing $|v_R|$ with time and moving away from U_2 . The same behavior is observed for a decrease in $|v_R|$ by similar arguments. Then, in this case, the point U_2 qualifies as unstable.

This type of stability analysis, by inspection of the function $g_R(v_R)$, can be carried over all the typical regions of multiplicity, and always the same conclusions are obtained. The unstable branches of the solution are represented by the intermediate branches of the solution, i.e., when, for a given d , there is an increasing sequence of possible solutions, $v_{R_{T1}}$, $v_{R_{T2}}$, $v_{R_{T3}}$, $v_{R_{T4}}$, $v_{R_{T5}}$ the branches containing the values with even indexes (in this case $v_{R_{T2}}$ and $v_{R_{T4}}$) are the unstable branches. The branches containing odd indexes are stable. This is true for the case of the "finger" or "isola" branches which appear at the top of the plots of Figures

Figure 4.19

Force ratio function g_R versus the absolute value of the relative velocity for different droplet sizes and fixed turbulence level ($u_{rms} = 2.5 \text{ m/s}$).

4.17-a through 4.18-b.

For certain regions of the curves, the branches are so close that for variations on U_G on the order of u_{rms} , the droplet velocity v_{RT} can jump from a stable branch to another. Consider a droplet of $1000\mu m$ in a annular flow field with $u_{rms} = 3.0 m/s$ (Figure 4.18-c). Assume that the particle achieved the largest of the three possible terminal velocities predicted. At this condition, say the particle velocity is v . Turbulent gas flow is accompanied by significant fluctuations in velocity. As eddies having different velocities sweep across the particle, the relative velocity changes. For example, if the local gas velocity increases the value of v_R will decrease, and the point moves down in the bifurcation diagram, eventually crossing the unstable branch. The reverse situation is also possible. This can imply the presence of a dynamic oscillatory behavior of some sort suggesting that a single measurable v_{RT} , may not be the expected observation. Torobin and Gauvin (1961) found very large scattering in the values of C_D calculated from measured values of v_R for conditions of Re close to Re_c . Clift and Gauvin (1971) mentioned the possibility of the existence of multiple solutions for v_{RT} , but the problem was never analyzed.

This stability analysis can only describe the behavior close to equilibrium. The behavior away from this situation can only be predicted by the integration of the equation of motion in conjunction with the gas flow field equations. Since this is a turbulent field, it represents an unsolved problem, aggravated in the case of annular flow, by the presence of a liquid film and droplets in a gas field. But the use of some simplifying assumptions, at least with respect to what happens in the gas flow field, can give a way to a solution of the equation of motion that can in part explain the experimentally observed results, as will be shown in next section.

4.3.4 Prediction of Droplet Velocities at the Center of the Column

The objective of this section is to predict the axial velocity of the droplets, v_z , measured at the center position ($r_M = 0$) of a column with the same pipe size and under conditions similar to the ones used during the experiments. In order to predict drop velocities from dynamic calculations, one must specify a time of flight. The drops originate at the liquid surface. At the centerline, all drops must have experienced a time of flight equal to the ratio of the radius to the radial velocity, which has been shown to be essentially constant. At any other position, $r_M \neq 0$, the time of flight, depends on the point of origin. For this reason, these computations are restricted to describing conditions at $r_M = 0$. The equation of motion, correspondent to this situation, can be obtained from Equation 4.43 to give:

$$\frac{dv_z}{dt} = \left(\frac{1-\gamma}{\gamma} \right) g - \frac{3}{2} \frac{1}{\rho_p} \nabla_z p - \frac{3}{4} \frac{1}{\gamma d} C_D(Re, I_R) |v_R| v_{Rz} , \quad (4.60)$$

$$\frac{dv_y}{dt} = 0 . \quad (4.61)$$

The initial conditions are:

$$v_z(t = 0) = v_{z_0} , \quad (4.62)$$

$$v_y(t = 0) = v_y , \quad (4.63)$$

where $\nabla_z p$ is the pressure gradient in the axial direction, v_R is the speed of the relative velocity vector, $\underline{v}_R$, and given in this case by $v_R = (v_y^2 + (v_z - U_G)^2)^{1/2}$. The system of ordinary differential equations, Equations 4.60 through 4.63, can then be solved, to obtain the time evolution of velocity in the presence of a turbulent stream by using Equations 4.50 through 4.55 for the drag law. In Equation 4.60, the total droplet acceleration is given by the sum of three acceleration terms:

- The *gravitational acceleration*, constant for incompressible gas flow, a condition satisfied here.
- The *gas pressure gradient acceleration*, depends directly on the gas flow through the conduit while the local values may vary due to the the turbulent motion of the gas. The average pressure gradient $\nabla_z \bar{p}$ is constant over a cross section of the column. The frequency of oscillation around the mean is high, and the droplets will not respond to these oscillations, and $\nabla_z p$ is replaced by $\nabla_z \bar{p}$.
- The *drag acceleration* requires a value for U_G in order to calculate v_R along the path. For purposes of precise computation, values of $U_G(r)$ would be required. However, in order to estimate the trends a single constant value of $U_G = 1.4U_{GS}$, the value over the center section of the core will be used.

Some important conclusions can be drawn from Equation 4.60 even before integration. Only the gravity term has a negative contribution to the total acceleration for the case of droplets moving upwards in annular flow. The gas pressure gradient acceleration acts positively. For conditions of the experiments of this study, this term represents only 10% of the gravity acceleration. But under other annular flow conditions, for instance, in the studies by Cousins and Hewitt (1968) where high pressure gradients were reported, this term can be twice as large as the gravity term. As a result it is possible to show that droplet velocities greater than the gas velocity can be expected.

The initial axial droplet velocity is assumed to be the velocity of the wave from where it originates. The radial component of $\underline{v}_0$ can be assumed to be the experimentally measured values of v_y . Recent experimental measurements by Zabaras (1985) of wave velocity in the same test section and in the same region of flow pa-

rameters suggest values for v_{z_0} on the order of 3 m/s. In the simulations presented here, v_y and v_{z_0} are varied around the values suggested experimentally to test the sensitivity of the results to these assumptions.

A solution of the system of Equations 4.60-4.63 is now possible. Namely, when U_{GS} and u_{rms} are considered constant, Equation 4.63 can be integrated by separation of variables, resulting in the following integral equation:

$$t - t_0 = \int_{v_{z_0}}^{v_z(t)} \frac{dv_z}{\left(\frac{1-\gamma}{\gamma}\right) g - \frac{3}{2} \frac{1}{\rho_p} \nabla_z \bar{p} - \frac{3}{4} \frac{1}{\gamma d} C_D(Re, I_R) |v_R| v_{Rz}}, \quad (4.64)$$

where

$$v_R = \left((v_z - U_G)^2 + v_y^2 \right)^{1/2}, \quad (4.65)$$

$$v_{Rz} = (v_z - U_G), \quad (4.66)$$

where $Re = (d |v_R| / \nu_f)$ and $I_R = (u_{rms} / |v_R|)$. In this way, the numerical handling of the discontinuities on the expressions for C_D , Equations 4.50-4.55, is simplified when a convenient quadrature procedure is used to evaluate the integral in Equation 4.64. The numerical procedure evolves in the following way:

- Set d , v_y and v_{z_0} .
- Find the time of flight t_F given from:

$$t_F = \left(\frac{D}{2v_y} \right). \quad (4.69)$$

- For a given v_{z_0} , a value of v_z is found by iteration until Equation 4.64 is satisfied.

In Figure 4.20 are plotted the results for $v_z(r_M = 0)$ as a function of the droplet diameter d , for a typical set of values of U_{GS} , v_{z_0} , v_r , with $\nabla_z \bar{p} = -550 \text{ N/m}^3$,

Figure 4.20

Axial velocity *versus* droplet size predictions at centerline for different levels of turbulence.

and with u_{rms} as a varying parameter. As can be observed, for $u_{rms} = 0$, a monotonically decreasing function of v_z is obtained. But as u_{rms} is increased to non-zero values, then the monotonicity of the solution disappears. The curves v_z versus d go through a minimum at lower values of d , then increase to a maximum and finally decrease slowly. The first minimum is associated with the *drag crisis* and Re_c . The large droplets are moving in the supercritical region of the C_D curve while the drag coefficient of the smallest droplets is controlled by the conditions for $Re < Re_c$.

Figure 4.21 shows the evolution of droplet velocity with radial position for different particle sizes, for the curve with $u_{rms} = 8.0$ m/s in Figure 4.20. The position of the C_D values in the drag curve can also be identified. For $d = 200$ μm , initially the droplet C_D values fall in the branch BC, before the critical region of the drag curve (Figure 4.13). This corresponds to a very rapid acceleration. As u_{rms} increases, then transition to the supercritical region takes place (branch CV), and the rate of acceleration decreases drastically. For the other particles traveling always in the supercritical region (branches CV, VM and MI), an almost constant rate of acceleration is found for the whole flight to the column center.

The position of the minimums in Figure 4.20 and the point of sudden change on the acceleration rates in Figure 4.21 is determined by the relationship of Re_c and I_R as expressed in Equations 4.44 and 4.45. If it had been possible to take into account the experimental observations of Wang (1969), that for high M_A the values of Re_c would be even smaller than the ones predicted, then the value of the minimum on the v_z versus d curve would be displaced to even lower values of d . In this case it would not be hard at all to find the similarity between the curves

Figure 4.21

Droplet axial velocity evolution with radial position for different droplet sizes.

in Figure 4.20 and the experimental results like the ones presented in Figures 4.9-a through 4.9-c.

A preliminary analysis of the influence of the shape of the drag curve on the velocity predictions was made. A different relationship Re_c versus I_R was tried:

$$Re_c = \frac{45}{I_R^2} , \quad (4.70)$$

based on a theoretical prediction by Torobin and Gauvin (1961), which predicts values for Re_c smaller than experimental Equations 4.45 and 4.46. Furthermore, since the branch CV, as was already explained, results from data scattering around Re_c , a single relationship between Re_c and Re_M was tried, as:

$$\log C_D = \frac{\log (0.3/C_{D_V})}{\log (Re_M/Re_c)} \log \left(\frac{Re}{Re_M} \right) + \log C_{D_V} , \quad (4.71)$$

where:

$$C_{D_V} = 0.3 \left(\frac{Re_c}{Re_V} \right) , \quad (4.72)$$

and Re_M and Re_V are obtained through the Equations 4.47 through 4.49. This new relationship simply connects the points $(Re_M, C_D(Re_M))$ and $(Re_c, C_D(Re_V))$ through a straight line.

The new predictions for the same conditions as in Figure 4.20 are presented in Figure 4.22. The changes observed are essentially a translation of the minimums of the curves to lower values of d , and even for $u_{rms} = 10.0 \text{ m/s}$ the curve present no minimum at all and has an aspect very similar to the experimentally obtained curves.

From the simulations made, it seems that a value around $u_{rms} = 8 \text{ m/s}$, would give a better agreement with the predictions of v_z for the larger droplets. There

Figure 4.22

Axial velocity *versus* droplet size predictions at centerline with modified drag curves at different levels of turbulence.

are no measurements of u_{rms} at present time in annular flow. For single phase pipe flow at the same Re_{GS} , it is observed that u_{rms} should be of the order of one to two times the values of the frictional velocity, u^* . For these experiments, u^* is of the order of 2 m/s, as will be shown in Chapter 5, and almost constant for all the flow conditions. In single phase pipe flow a maximum expected value of u_{rms} would be of the order of 4 m/s. But the level of turbulence of the gas phase is expected to be higher for two-phase than for single phase flow. The reason is twofold: first the gas is not contained inside rigid walls but inside a highly turbulent liquid film; second the presence of droplets create wakes and vortices can be expected to cause an increase in the velocity fluctuations.

To determine how v_{z0} , v_y , U_{GS} , and $\nabla_z \bar{p}$ affect the v_z versus d curves, a systematic simulation was made by varying these quantities between typical values. The minimum and maximum possible values of $\nabla_z \bar{p}$ in the range of the experiments were used in this simulation ($\nabla_z \bar{p} = -550$ to -950 N/m³ from Zabaras, 1985). The solutions obtained were almost insensitive to these values, so only the results with $\nabla_z \bar{p} = -550$ are reported.

In Figure 4.23, the dependence on U_{GS} is shown. A shift in the maximum towards higher values of d takes place when U_{GS} is increased. This is consistent with the experimental observations. Only at the lowest gas rate was a maximum observed. At higher rates the maximum disappears, since the sizes corresponding to these maximums are unstable and not observable. The dependence on gas velocity is more pronounced for larger particles as observed experimentally. Certainly it is true that the behavior predicted for the smallest droplets was not found. This is due to the reasons explained above on the dependence of Re_c on I_R and M_A .

Figure 4.23

The influence of gas rates on droplet axial velocity at centerline

Figure 4.24

The influence of droplet radial velocity on droplet axial velocity at centerline

The dependence on v_y is represented in Figure 4.24. Again a strong dependence is observed for larger values of d . Observe that the values of v_y used correspond to double the flying time for each successive curve. The larger t_F corresponds to $v_y = 0.5 \text{ m/s}$.

Finally the dependence on the initial velocity v_{z0} is represented in Figure 4.25. A weak dependence on this parameter is observed. This reveals that most of the droplet acceleration is made in the initial moments of the droplet flight and if the droplet flight is long enough the velocities observed are weakly dependent on v_{z0} .

In all the simulations reported, the particles never achieved equilibrium except for droplets with $d < 200 \text{ }\mu\text{m}$. At equilibrium the denominator in Equation 4.64 is equal to zero and in this case the integrand in Equation 4.64 presented a singularity, which makes this equation unsolvable.

As was mentioned before, the Basset terms and added mass terms were estimated and compared with the terms used in Equation 4.64. They were estimated with the expressions on Equation 4.41, using the solution obtained through Equation 4.64. The added mass terms found are totally negligible. The Basset terms are also negligible, during the initial motion, but become significant near the equilibrium, as the particles approach their terminal velocities. This only happens for very small particles.

In summary, it can be stated that the observed dependence of C_D on both Re and turbulence level rationalizes the experimental observations, namely: (a) v_z increases with d over a certain size range and displays a maximum; and (b) v_z is only weakly dependent on U_{GS} . However the quantitative behavior can not be described until reliable and general curves of $C_D(Re, I_R)$ are available. This is

Figure 4.25

The influence of initial droplet velocity on droplet axial velocity at centerline

clearly the next task.

Chapter 5

Droplet Entrainment and Its Contribution to Momentum Transfer

5.1 Introduction

In this Chapter, a quantitative assessment of the importance of the droplet entrainment on momentum loss in annular flow will be made. This will be obtained by incorporating the droplet contribution in the momentum balance equations.

The process of droplet entrainment in annular flow occurs in three basic steps:

- Droplet generation from the wavy film. The initial drop axial velocity is equal to the velocity of the wave from which it was generated.
- Droplet flight in the gas core where the drop is carried by the entraining gas. Momentum is transferred from the gas to the droplet resulting in an increase of the drop velocity, u . There is the possibility of droplet break-up or coalescence.
- Droplet deposition, resulting from the final impact of the droplet upon the liquid film on the the tube wall.

For the case of *equilibrium annular flow*, which is under study, the rates of deposition and entrainment are equal. Therefore, only the study of one of the rates is necessary.

In Section 5.2, a model will be developed that permits the computation of the rates of deposition. The basic assumption is that the droplets, during their flight in the gas core, have a rectilinear trajectory, which will be shown to be close to the real situation. Once this is accepted, then it is shown that the deposition rates are mainly determined by the angular distribution of drop velocity, which was measured experimentally. The values of the deposition mass transfer coefficients obtained in this way are compared with other experimental data in Section 5.3.

From the rates of entrainment or deposition along with accelerations calculated from the data, it is possible to show that the momentum transfer to the drops can account for a substantial part of the observed pressure drop. Knowing the momentum transfer due to the drops, it is then possible to calculate and analyze the frictional contribution to the pressure gradient.

5.2 Development of a Deposition Model

5.2.1 The Trajectory of a Droplet in the Gas Core

The trajectories of droplets, $\underline{x}(t)$, can be obtained by solving the dynamic equations (Equations 4.19 and 4.20) simultaneously, once a drag law and the initial conditions ($\underline{x}(0)$; $\underline{v}(0)$) are chosen. In Figure 5.1, typical results for different droplet

Figure 5.1
Droplet trajectories for different values of the initial velocity, $v_z(0)$.

sizes, using the modified drag law presented at the end of Section 4.3.2, are presented. Different initial droplet velocities are used for each graph and, as suggested by the experimental results, a constant lateral, $v_y = 1.0 \text{ m/s}$, velocity was used.

As can be observed from these results, the droplet trajectory is almost linear. Note that the axial and radial scales in this figure are in the same proportion as the experimental apparatus geometry. This linearity can be explained by the constancy of the radial velocity and by the fact, already pointed out in Section 4.3.4, that most of the droplet acceleration is observed in the initial period of the droplet flight, when the relative velocity is extremely high.

At any point of the droplet trajectory, the relative direction of the droplet flight can be characterized by the droplet axial directional coordinate, the angle, θ , defined as:

$$\theta = \frac{\pi}{2} - \left| \arctan \left(\frac{v_z}{v_y} \right) \right|, \quad 0 \leq \theta \leq \frac{\pi}{2}. \quad (5.1)$$

For the cases in Figure 5.1, for the selected pairs of v_{z0} and v_y the initial angle corresponds to 45° , 18° , and 11° , respectively. In the same figure, the values of θ at the centerline are indicated. These values are different from the initial one, but, by inspection of the trajectories, it can be observed that the values at the center position are comparable to the values observed in most of the droplet flight.

Besides this theoretical argument, it will be shown in subsequent sections that the droplet angle distribution is almost independent of the radial position, which is an indication of a linear trajectory. Furthermore, as was already shown in Chapter 4, the droplet motion for the sizes commonly measured in annular flow is controlled mainly by their own inertia, and, therefore, are not directly affected by the turbulent gas fluctuations, which would impose a tortuous trajectory.

5.2.2 Deposition Rate of Droplets

Consider any cross section of a column at a distance z_0 from the entrance, as in the sketch of Figure 5.2, with an average area A_{z_0} . At $z > z_0$ droplets which deposit have two specific origins: either they originate at $z < z_0$ and deposit in the distance L_D , or they are entrained in the region $z > z_0$ and also deposit in that region. The objective here is to find the mass flow rate of droplets, $W_D(L_D)$, which deposit within a distance L_D in the axial direction of the flow after crossing the cross section located at z_0 .

All the droplets that contribute to $W_D(L_D)$ must pass through the cross section A_{z_0} . Thus, A_{z_0} can be viewed as a domain of droplet point sources, S_{z_0} . Each individual point source, S_{z_0} , is referenced by a set of cylindrical coordinates (z_0, r, ϕ) relative to the column axis and a particular volumetric flux rate of droplets $U_{S_{z_0}}(r, \phi)$.

From each source, $S_{z_0}(r, \phi)$, droplets are generated with random directions and speeds. The directions are defined by the local spherical coordinates, ζ and θ , of the droplet velocity vector, $\underline{v}$, as depicted in Figure 5.3. The range of the source and the droplet coordinates is given by:

<u>Source Coordinates</u>	<u>Droplet Local Directional Coordinates</u>
$0 \leq z_0 \leq L$	$0 \leq \zeta \leq 2\pi$
$0 \leq r \leq (D - 2\bar{m})/2$	$0 \leq \theta \leq \pi/2$
$0 \leq \phi \leq 2\pi$	

where D is the column diameter, L is the column length, and $\bar{m}$ is the average liquid film thickness.

Figure 5.2

Schematic representation of annular flow: the cross reference section A_{z_0} ; and deposition length L_D .

With these new coordinates, $W_D(L_D)$ can be expressed as a surface integral:

$$W_D(L_D) = \int_{A_{z_0}} \rho_l U_{S_{z_0}}(r, \phi) F_D^V(r, \phi, L_D) dA, \quad (5.2)$$

where $F_D^V(r, \phi, L_D)$ is a function representing the volumetric fraction of the droplets generating from $S_{z_0}(r, \phi)$ and which deposit within a distance L_D from the reference cross section A_{z_0} .

The function $F_D^V(r, \phi, L_D)$ can be related to the joint volume probability density function of the directional angles, $f_{\theta\zeta}^V$, by the following integral relationship:

$$F_D^V(r, \phi, L_D) = 1.0 - \int_0^{2\pi} \int_0^{\theta_D(r, \zeta, L_D)} f_{\theta\zeta}^V d\theta' d\zeta', \quad (5.3)$$

where $\theta_D(r, \zeta, L_D)$ is the axial directional angle, above which value droplets generating from a source of radius r and traveling with an angular radial direction ζ , are deposited within a distance L_D . It is possible to obtain the relationship only if the trajectories are assumed to be rectilinear. In addition, $f_{\theta\zeta}^V$ can be also a function of position.

A simple trigonometric relationship can be found between θ_D and two other variables: the deposition distance, L_D , and the distance, l , of the source $S_{z_0}(r, \phi)$ from the wall, measured in the ζ -direction of the trajectory as sketched in Figure 5.3:

$$\theta_D = \frac{\pi}{2} - \arctan\left(\frac{L_D}{l}\right). \quad (5.4)$$

The relationship between l and r and ζ can be found after some algebraic manipulations:

$$l = 2R_c \left\{ \left(\frac{r}{R_c}\right) \cos(\zeta) + \sqrt{1 - \left(\frac{r}{R_c}\right)^2 + \left[\left(\frac{r}{R_c}\right) \cos(\zeta)\right]^2} \right\}, \quad (5.5)$$

Figure 5.3

Schematic representation of a droplet source, and its directional coordinates.

where

$$R_c = \frac{1}{2}(D - 2\bar{m}) = \frac{1}{2}D_c . \quad (5.6)$$

A functional form for $f_{\theta\zeta}^V$ is necessary to compute F_D^V through Equation 5.3. Assuming that θ and ζ are independent variables in a statistical sense, then $f_{\theta\zeta}^V$ can be obtained once the individual volumetric density functions, f_θ^V and f_ζ^V , are known, that is:

$$f_{\theta\zeta}^V = f_\theta^V f_\zeta^V . \quad (5.7)$$

This assumption is easily verified since droplets passing through any point source are generated from all radial directions. Furthermore, for each radial direction ζ , droplets can originate from any axial direction, θ , upstream of A_{z_0} .

Another simplifying assumption is that f_ζ^V is a uniform distribution, i.e., there is symmetry under rotation over ζ . This implies that:

$$f_\zeta^V(\zeta') = \frac{1}{2\pi} , \quad 0 \leq \zeta' \leq 2\pi . \quad (5.8)$$

Replacing 5.8 into 5.7 results in:

$$f_{\theta\zeta}^V(\theta', \zeta') = \frac{1}{2\pi} f_\theta^V(\theta') , \quad (5.9)$$

and using this result in Equation 5.3, a simplified expression for F_D^V is obtained:

$$F_D^V(r, \phi, L_D) = 1.0 - \frac{1}{2\pi} \int_0^{2\pi} \int_0^{\theta_D(r, \zeta, L_D)} f_\theta^V(\theta') d\theta' d\zeta' . \quad (5.10)$$

The inner integral expresses the volumetric distribution function of θ , F_θ^V , thus:

$$F_D^V(r, \phi, L_D) = 1.0 - \frac{1}{2\pi} \int_0^{2\pi} F_\theta^V(\theta_D(r, \zeta', L_D)) d\zeta' . \quad (5.11)$$

Replacing Equation 5.11 into Equation 5.2, gives, after some manipulation:

$$W_D(L_D) = \int_0^{2\pi} \int_0^{R_c} \rho_l U_{S_{z_0}}(r', \phi') r' dr' d\phi' - \frac{1}{2\pi} \int_0^{2\pi} \int_0^{R_c} \int_0^{2\pi} \rho_l U_{S_{z_0}}(r', \phi') F_\theta^V[\theta_D(r', \zeta', L_D)] r' d\zeta' dr' d\phi' , \quad (5.12)$$

The first integral represents the total mass flow rate, through A_{z_0} of droplets entrained, W_{LE} . For the second integral, it will be assumed that $U_{S_{z_0}}$ is a constant, independent of position, and given by:

$$U_{S_{z_0}}(r, \phi) = \frac{W_{LE}}{\rho_l A_{z_0}} . \quad (5.13)$$

This assumption is based on experimental data presented by Gill *et al.* (1964), where liquid flux-rates were measured in the gas core of annular flow in a 32 mm diameter column. An almost constant flux profile was found in the central region of the gas core. Towards the wall, an increase in the liquid flux was observed, but according to the authors, this resulted from the contact between the sampling probe and the liquid film surface waves.

Replacing 5.13 into 5.12 and rearranging.

$$W_D(L_D) = W_{LE} \left\{ 1.0 - \frac{1}{A_{z_0}} \int_0^{R_c} \int_0^{2\pi} r' F_\theta^V[\theta_D(r', \zeta', L_D)] d\zeta' dr' \right\} . \quad (5.14)$$

The expression between parentheses represents the mass fraction of droplets that cross A_{z_0} and deposit within a distance L_D . This term will be referred as $X(L_D)$, and Equation 5.14 becomes:

$$W_D(L_D) = W_{LE} X(L_D) . \quad (5.15)$$

Therefore the rate of deposition of drops, $W_D(L_D)$, can be computed as long as the rate of flow of entrained drops, W_{LE} , is known. This can be measured experimentally, and $X(L_D)$ computed. To evaluate $X(L_D)$ an integration of F_θ^V is necessary. To this end an analytical function for F_θ^V is proposed in the next section.

5.2.3 A Model for the Angle Volume Density Function

The axial directional angle, θ , is a one sided variable extending from 0 to $\pi/2$. In order to introduce a convenient density function, a new angle, η , is defined, related to θ , through:

$$|\eta| = \theta \quad ; \quad -\frac{\pi}{2} \leq \eta \leq \frac{\pi}{2} . \quad (5.16)$$

This variable contains the information about the relative direction of movement of the droplet with respect to the axis of the column, and can be associated with a gaussian distribution, expressed as:

$$f_{\eta}^V(\eta') = \frac{1}{\sqrt{2\pi}s_{\eta}} \exp \left[-\frac{1}{2} \left(\frac{\eta' - \bar{\eta}}{s_{\eta}} \right)^2 \right] , \quad (5.17)$$

where $\bar{\eta}$ is the average value of η and s_{η} is its standard deviation. Since, as was already assumed in the previous section, there is symmetry under rotation of ζ , then the only possible value for $\bar{\eta}$ is zero. Hence:

$$f_{\eta}^V(\eta) = \frac{1}{\sqrt{2\pi}s_{\eta}} \exp \left[-\frac{1}{2} \left(\frac{\eta}{s_{\eta}} \right)^2 \right] . \quad (5.18)$$

In order to obtain f_{θ}^V from Equation 5.18, it is necessary to apply the transformation of variables given by Equation 5.16. Since this is not a one to one correspondence, the theorem of statistics used in Chapter 3 (Equation 3.15) can not be used directly, but a modified theorem for this case, (Papoulis, 1965, page 126), relates the two density functions, through:

$$f_{\theta}^V(\theta) = \frac{2}{|1|} f_{\eta}^V(\eta) , \quad (5.19)$$

and replacing Equation 5.18 into Equation 5.19, finally gives:

$$f_{\theta}^V(\theta) = \frac{2\delta^*}{\sqrt{\pi}} \exp \left[-(\delta^*\theta)^2 \right] , \quad \delta^* = \frac{1}{\sqrt{2}s_{\eta}} . \quad (5.20)$$

This is a single parameter model that can be tested against experimentally measured values of f_{θ}^V . The relationship between the parameter δ^* and the average angle, $\bar{\theta}_V$, can be obtained through:

$$\bar{\theta}_V = \int_0^{\infty} \theta' f_{\theta}^V(\theta') d\theta' = \frac{2\delta^*}{\sqrt{\pi}} \int_0^{\infty} \theta' \exp\left[-(\delta^* \theta')^2\right] d\theta' = \frac{1}{\delta^* \sqrt{\pi}}, \quad (5.21)$$

and the standard deviation, s_{θ_V} , is related to δ^* , through:

$$s_{\theta_V} = \left(\overline{\theta_V^2} - \bar{\theta}_V^2\right)^{\frac{1}{2}} = \left(\frac{1}{2\delta^{*2}} - \frac{1}{\pi\delta^{*2}}\right)^{\frac{1}{2}} = \frac{1}{\delta^*} \left(\frac{\pi-2}{2\pi}\right)^{\frac{1}{2}}. \quad (5.22)$$

The experimental density functions, f_{θ}^V , were obtained from the simultaneous measurement of the droplet diameter and two velocity components, obtaining θ through Equation 5.1. The statistical methods used are described in Chapter 2, and the results are presented in Appendix A.2. A summary of the experimental values of $\bar{\theta}_V$ and s_{θ_V} obtained at different gas and liquid flow rates and at different radial positions can be found in Table 5.1 and Figure 5.4.

From the analysis of Table 5.1, and, as is clearly illustrated in Figure 5.4, the values of $\bar{\theta}_V$ at the center position are almost independent of the gas and liquid rates, presenting an average value of $\bar{\theta}_V = 8.5^\circ$. From the statistical analysis of the droplet angle presented in Appendix A.3, it is observed that there is a consistent trend of decreasing angles of flight as the droplet size increases. An increase in gas velocity should result in a decrease of the angle, since v_z increases, and based on experimental observations, v_y remains essentially constant. However, an increase in gas velocity causes a larger fraction of smaller droplets with larger values of θ . This compensates in such a way that $\bar{\theta}_V$ remains nearly independent of the gas rates. The independence of the liquid rates has already been discussed in Chapter 4.

Table 5.1

Summary of experimental and theoretical statistical parameters
for the angle distribution.

Exp #	U_{GS} (m/s)	U_{LS} (m/s)	r_M (cm)	N	$\bar{\theta}_V \pm e_{95}^\theta$ (deg)	s_{θ_V} (deg)	$\bar{\theta}_V^*$ (deg)	$s_{\theta_V}^*$ (deg)	δ^* (deg ⁻¹)
24	14.0	0.034	0.0	554	8.43 ± 0.55	6.6	8.57	6.5	0.067
23	15.9	0.034	0.0	577	7.37 ± 0.54	6.7	7.72	5.8	0.076
22	17.8	0.034	0.0	579	7.81 ± 0.49	6.0	7.61	5.7	0.072
21	19.5	0.034	0.0	621	8.03 ± 0.48	6.1	7.92	5.9	0.071
31	21.6	0.034	0.0	576	9.11 ± 0.54	6.6	9.30	7.0	0.062
26	24.7	0.034	0.0	676	9.21 ± 0.50	6.6	9.37	7.1	0.061
34	14.5	0.069	0.0	568	9.63 ± 0.53	6.4	9.47	7.2	0.059
33	17.5	0.069	0.0	573	9.17 ± 0.58	7.1	9.60	7.3	0.061
30	21.5	0.069	0.0	588	8.41 ± 0.53	6.6	8.50	6.4	0.067
28	24.7	0.069	0.0	590	8.28 ± 0.49	6.1	8.19	6.2	0.068
25	14.1	0.121	0.0	583	7.70 ± 0.52	6.3	8.14	6.2	0.073
32	17.1	0.121	0.0	580	8.20 ± 0.50	6.2	8.22	6.2	0.069
29	21.5	0.121	0.0	585	8.91 ± 0.53	6.5	9.07	6.9	0.063
27	24.5	0.121	0.0	585	8.37 ± 0.51	6.3	8.41	6.4	0.067
40	24.6	0.034	2.0	577	7.93 ± 0.50	6.1	7.99	6.0	0.071
43	24.8	0.034	1.0	587	8.61 ± 0.52	6.4	8.70	6.6	0.066
26	24.7	0.034	0.0	676	9.21 ± 0.50	6.6	9.37	7.1	0.061
41	24.4	0.121	2.0	538	8.14 ± 0.55	6.5	7.90	6.0	0.070
42	24.6	0.121	1.0	590	9.58 ± 0.53	6.6	9.73	7.4	0.059
27	24.5	0.121	0.0	585	8.37 ± 0.51	6.3	8.41	6.4	0.067
46	17.7	0.034	1.5	530	11.24 ± 0.79	9.2	11.59	8.8	0.050
44	17.7	0.034	1.0	577	8.66 ± 0.56	6.9	8.86	6.7	0.065
27	17.8	0.034	0.0	579	7.81 ± 0.49	6.0	7.61	5.7	0.072
47	17.5	0.121	1.5	522	10.40 ± 0.69	8.0	10.23	7.7	0.054
45	17.5	0.121	1.0	547	8.49 ± 0.53	6.3	8.29	6.3	0.066
32	17.1	0.121	0.0	580	8.20 ± 0.50	6.2	8.22	6.2	0.069

Figure 5.4

Experimental values of average angle, $\bar{\theta}_v$, versus U_{GS} , for different values of U_{LS} .

The values of $\bar{\theta}_V$ obtained at different radial positions are plotted for different values U_{GS} and U_{LS} in Figure 5.5. For the largest gas rate a flat profile, liquid rate independent, is observed. For the lower gas rate an increase of $\bar{\theta}_V$ is found for the positions closer to the wall possibly revealing that, for this low gas rate, the acceleration is smaller and a dependence on the radial position is observed. But due to the flatness of the profiles and for the sake of simplicity, the profiles will be assumed to be flat and $\bar{\theta}_V$ equal to the one observed at the center position.

The model of f_θ^V , proposed by the Equation 5.20, was tested against the experimental density functions given in Appendix A.2 and a value of δ^* which minimizes the χ^2 -statistics was chosen as explained in Chapter 2. The corresponding theoretical values of $\bar{\theta}_V^*$ and $s_{\theta_V}^*$ are tabulated in Table 5.1. The average absolute deviation from the experimental values of $\bar{\theta}$ is 2%, and the maximum deviation is 5%. For the values of s_{θ_V} , the average absolute deviation is 5%, and the maximum is 14%. Figure 5.6 shows the experimental density functions plotted against the theoretical model for different gas and liquid rates at the center position. A generally good agreement is observed.

Summarizing the results of this analysis, which will be carried over to the development of the deposition model:

- The model of f_θ^V as expressed by Equation 5.20 seems the appropriate one to use.
- The values of $\bar{\theta}_V$ appear to be independent of the radial positions, resulting in a constant f_θ^V over the cross section, A_{z_0} .
- The value of $\bar{\theta}_V$ seems to be essentially independent of the gas and liquid rates, for the range of fluid rates used in this work, and has an approximately constant

Figure 5.5
Experimental radial profiles of $\bar{\theta}_v$ for different values of U_{GS} and U_{LS} .

value of 8.5° . However, for any one liquid and gas rate θ_V varies with drop size.

5.2.4 Final Form of the Deposition Model

If Equation 5.20 is accepted as a model of f_θ^V , then the distribution function F_θ^V in Equation 5.14 can be computed:

$$F_\theta^V(\theta_D) = \int_0^{\theta_D} f_\theta^V(\theta') d\theta' = \int_0^{\theta_D} \frac{2\delta^*}{\sqrt{\pi}} \exp[-(\delta^* \theta')^2] d\theta' = \text{erf}(\delta^* \theta_D). \quad (5.23)$$

Replacing this result into Equation 5.14, and expressing X through Equation 5.15, results in:

$$\begin{aligned} X(L_D) &= \frac{W_D(L_D)}{W_{LE}} \\ &= 1.0 - \frac{1}{A_{z_0}} \int_0^{R_c} \int_0^{2\pi} r' \text{erf}[\delta^* \theta_D(r', \zeta', L_D)] d\zeta' dr', \end{aligned} \quad (5.24)$$

which, in conjunction with Equations 5.4, 5.5, 5.6 and 5.15, represent the final form of the deposition model.

In Figure 5.7 the values of $X(L_D)$, the fraction of the droplets crossing any plane which are deposited in a distance L_D downstream, are plotted against the dimensionless distance, L_D/D , for different values of $\bar{\theta}_V$. An important observation is the distance the droplets travel inside the gas core and their deposition distribution in mass terms. For instance, for $\bar{\theta}_V \approx 9^\circ$, 50% of the mass of droplets deposits within a distance equivalent to 3 tube diameters, and, at a distance of 18 diameters, only 10% of the initial mass is still traveling in the gas core. Since the experimentally measured values of $\bar{\theta}_V$ varied narrowly between 8° to 10° , the deposition distribution function is almost constant. This is especially so since $X(L_D)$

Figure 5.6
Experimental and theoretical angle probability density functions,
 f_θ^V .

is not strongly dependent on $\bar{\theta}_V$ for $\bar{\theta}_V > 8^\circ$, as can be observed in Figure 5.7. The function, $X(L_D)$, only gives partial information on the deposition transfer. The goal is to find the total rate of deposition which provides knowledge of the rate of droplet entrainment in equilibrium annular flow. In the next section, $X(L_D)$ will be related to the total deposition rate, and the predicted values will be compared with experimental results.

5.3 Rates of Droplet Deposition

5.3.1 The Relationship Between $W_D(L_D)$ and N_D

In the region of equilibrium annular flow, the mass flux of droplets depositing on the liquid film, N_D , is constant along the tube. Therefore, the total mass flow rate of droplets depositing at a distance L_D , $W_D^T(L_D)$, can be expressed as:

$$W_D^T(L_D) = N_D \pi D_c L_D . \quad (5.25)$$

This function can be viewed as the sum of two other functions: i) the rate of deposition of droplets crossing the plane A_{z_0} , $W_D(L_D)$; and ii) the rate of deposition of droplets that are entrained after A_{z_0} , which will be referred as $W_D^{RE}(L_D)$. Therefore:

$$W_D^T(L_D) = W_D(L_D) + W_D^{RE}(L_D) . \quad (5.26)$$

For any value of L_D , $W_D(L_D) \geq W_D^{RE}$. In particular, for small values of L_D , the total rate of deposition has no contribution from the droplets entrained after A_{z_0} ,

Figure 5.7

Fractional deposition, X , versus deposition length, L_D , for different values of $\bar{\theta}_V$.

as they will have to travel in the ζ -direction with a finite radial velocity. Therefore, $W_D(L_D) \gg W_D^{RE}(L_D)$, and Equation 5.26 can be approximated by:

$$W_D^T(L_D) = W_D(L_D), \quad \text{for small } L_D. \quad (5.27)$$

Then:

$$\begin{aligned} \left. \frac{d}{dL_D} W_D^T \right|_{L_D \rightarrow 0} &= \left. \frac{d}{dL_D} (N_D \pi D_c L_D) \right|_{L_D \rightarrow 0} \\ &= N_D \pi D_c = \left. \frac{d}{dL_D} W_D \right|_{L_D \rightarrow 0}, \end{aligned} \quad (5.28)$$

or:

$$N_D = \frac{1}{\pi D_c} \left. \frac{d}{dL_D} W_D(L_D) \right|_{L_D \rightarrow 0}, \quad (5.29)$$

where N_D can be seen to be the lateral deposition flux at any position along the tube. Replacing Equation 5.25 in Equation 5.29:

$$N_D = \frac{W_{LE}}{\pi D_c} \left. \frac{d}{dL_D} X(R_c, \delta^*) \right|_{L_D \rightarrow 0}. \quad (5.30)$$

Thus, once W_{LE} , D_c , and δ^* or $\bar{\theta}_V^*$ are obtained from experiments, the values of N_D can be computed. Furthermore, N_D can be related to the mass transfer coefficient, K_D , which is commonly reported in the literature, through the definition:

$$N_D = K_D \frac{\rho_g W_{LE}}{W_G}, \quad (5.31)$$

where ρ_g is the density of the gas core and W_G is the gas mass flow rate. Then, K_D relates to X , through:

$$K_D = \frac{W_G}{\pi D_c \rho_g} \left. \frac{d}{dL_D} X(R_c, \delta^*) \right|_{L_D \rightarrow 0}, \quad (5.32)$$

which can be rearranged to express the dimensionless quantity, K_D/U_{GS} , as:

$$\frac{K_D}{U_{GS}} = \frac{D_c}{4} \left. \frac{d}{dL_D} X(R_c, \delta^*) \right|_{L_D \rightarrow 0}, \quad (5.33)$$

where U_{GS} is computed over the cross sectional area of the gas core, although, generally, for small film thickness ($D \gg \bar{m}$), D_c can be approximated by D . It can be seen that $4K_D/D_c U_{GS}$ is simply the slope of the curves in Figure 5.7 at the origin. This depends uniquely on $\bar{\theta}_V$ for a given D_c . For different values of D_c , the slope at the origin is inversely proportional to D_c for a given value of $\bar{\theta}_V$. A single curve, K_D/U_{GS} versus δ^* , independent of D_c , was found and is presented in Figure 5.8.

5.3.2 Prediction and Comparison with Experimental Data

Table 5.2 presents the values of K_D computed from the experimental data obtained in this work. The values of $(dX/dL_D)|_{L_D \rightarrow 0}$ were obtained from Figure 5.8 with $D_c = D$. Previous experimental data on K_D values have been reviewed by McCoy and Hanratty (1977). The available data sources for vertical turbulent flow at the present time are shown in Table 5.3. It should be noted that, at the exception of the work of Cousins and Hewitt (1968), most of the data is based on the use of injected particles in a turbulent pipe flow. All the values of K_D reported in these papers were obtained through direct measurements. Not listed in the table are the experimental measurements based on the tracer techniques by Quandt (1965), Cousins *et al.* (1965), Jagota *et al.* (1973), and Andreussi (1983). With this method the reported values of K_D depend strongly on the assumption of perfect mixing of the liquid film and the gas phase, an assumption which is questionable.

The comparison with other data is made by plotting the dimensionless quantity K_D/u^* , where u^* is the gas frictional velocity, versus a dimensionless particle

Figure 5.8
 K_D/U_{GS} versus δ^* , as computed from Equation 5.24.

Table 5.2
Summary of values of K_D , based on the experimental data obtained in this work

Re_{LS}	U_{GS} (m/s)	ρ_g (Kg/m ³)	Re_{GS}	$\bar{d}_{10}$ (μm)	u^* (m/s)	δ^* (deg ⁻¹)	K_D (m/s)	K_D/u^*	τ^+
1684	14.0	1.30	52000	759	1.95	0.067	0.682	0.350	5.0×10^5
1684	15.9	1.30	58000	731	1.98	0.077	0.677	0.342	4.6×10^5
1684	17.8	1.30	65000	585	2.00	0.072	0.804	0.402	3.0×10^5
1684	19.5	1.32	72000	613	2.01	0.070	0.905	0.450	3.4×10^5
1684	21.6	1.37	82000	491	2.03	0.062	1.140	0.561	2.2×10^5
1684	24.7	1.38	95000	423	2.11	0.061	1.310	0.623	1.8×10^5
3350	14.5	1.29	52000	791	2.02	0.059	0.807	0.399	5.5×10^5
3350	17.4	1.20	64000	647	1.98	0.062	0.922	0.466	3.7×10^5
3350	21.6	1.37	82000	467	2.03	0.067	1.050	0.518	2.0×10^5
3350	24.7	1.38	96000	462	2.10	0.068	1.180	0.564	2.2×10^5
6120	14.1	1.33	52000	763	1.97	0.073	0.628	0.310	4.9×10^5
6120	17.1	1.33	64000	744	1.95	0.069	0.810	0.416	4.8×10^5
6120	21.5	1.38	83000	636	2.00	0.063	1.110	0.553	3.8×10^5
6120	24.5	1.39	96000	550	2.08	0.068	1.190	0.570	3.2×10^5

Table 5.3

Summary of published deposition studies in vertical flow.

Source	Symbol	Flow Direction	Particle Size Range (μm)	Particle Material	ρ_p/ρ_g	Gas Velocity Range (m/s)	Tube Diameter (mm)
Friedlander & Johnstone (1957)	●	upward	0.8-2.63**	iron aluminum	6100 2093	7.3-54.9 0.404-1.44	5.4-25.4 13.8
Schwendiman & Postma (1961)	+	upward	2-4**	zinc sulfide	2744	2.16-17.7	19.1
Wells & Chamberlin (1967)	△	upward	0.65-2.1**	tricresol phosphate	915	1.76-29.9	12.7
Cousins & Hewitt (1968)	▲	upward	70-204*	water	775	23.8-41.5	9.5
Schmel (1968)	○	upward	1-8**	uranine methylene blue	1163	5.09-36.6	53.0-29.3
Farmer (1969)	▽	downward	100-260*	water	775	16.8-33.8	12.7
Ilori (1971)	▼	upward	6-9**	80% methylene 20% uranine	1317	2.40-24.0	29.8
Jagota <i>et al</i> (1973)		upward	—	polystyrene water	775 775	7.6-27.6 11.8-30.5	12.7 25.4
Liu & Agarwal (1974)	■	downward	1.4-21**	olive oil uranine	713	11.0-55.0	12.7
Forney & Spielman (1974)	×	downward	19.5 30.9 32.0 48.5	ragweed pollen lycopodium spores polystyrene pecan pollen	372 504 852 728	14.8-45.0 7.24-30.2 11.8-23.6 11.8-24.1	13.0-36.5 13.0-44.0 25.4 17.8-25.4

* Volume mean diameter

** Uniform diameter

relaxation time, τ^+ , defined as:

$$\tau^+ = \frac{1}{18} \frac{\rho_g}{\rho_g} \left(\frac{\rho_g u^* d}{\mu_g} \right)^2, \quad (5.34)$$

where d , the particle diameter, is taken as $\bar{d}_{10}$. The choice of these two dimensionless numbers results from dimensional analysis. The experimental values of K_D/u^* and τ^+ can be found in Table 5.2. The values of u^* were obtained from the experimental correlation developed in Section 5.4. These data are plotted in Figure 5.9, together with data from other sources tabulated in Table 5.2.

It can be observed that the values found in the present work are consistent with other data reported for large values of τ^+ . This corresponds to larger particles where the inertia of the particles is controlling. In this region, there is an almost constant value of K_D/u^* . For smaller values of τ^+ , a stronger dependence of K_D/u^* with τ^+ is observed, revealing a strong influence of the turbulence diffusion. Therefore, the inclusion of the data of the present work reinforces the idea (McCoy and Hanratty, 1977) that for $\tau^+ > 10^2$ there exists an independence of K_D/u^* on τ^+ , and the values of K_D/u^* obtained from the present model are in close agreement with other data.

If the data are reported in terms of fractional rate of deposition, X versus L_D/D , then the validity of the model can be evaluated through Equation 5.24. This equation contains only one independent parameter, δ^* (or $\bar{\theta}_V$ via Equation 5.21). A search for the single value of δ^* which gives the best fit can be made, and then it can be observed how good the fit is over the entire X versus L_D/D curve.

Cousins and Hewitt (1968) present experimental results in vertical annular flow. Figure 5.10 shows three curves of their measured X versus L_D for two different pipe sizes and different flow rates. These experiments were designed to avoid

Figure 5.9

Deposition rates of published data (McCoy and Hanratty, 1977), plus experimental values from the present work.

reentrainment. In each case a value of δ^* was found by a least-squares technique to Equation 5.24. The curves of Figure 5.10 represent the predicted results.

The impressive fact is that a single parameter model can predict the behavior over the full range of L_D values. This result is superior to predictions of Hutchinson *et al*, (1971) with these same data. In their work a diffusion process was used as the basic mechanism. It is clear from their results that a single set of parameter values cannot express the $X(L_D/D)$ curve.

This result is additional evidence that, in annular flow due to the size of the particle, the droplet inertia controls the droplet dynamics. This is in agreement with the basic assumption that linear trajectories exist rather than the idea that tortuous trajectories exist as predicted by diffusion type models. Furthermore, the theoretical values of K_D , calculated from Equation 5.32 for these data, are in close agreement with the experimental values calculated from the data by McCoy and Hanratty (1977). Therefore, the present model not only predicts the correct behavior of the $X(L_D)$ curves, but it also gives values of K_D which are very close to values suggested experimentally.

The importance of the validation of this simple model, is that, now it is possible to compute the mass transfer rates of droplets, based on experimental measurements of angle distributions. By using the present technique, there is no interference with the flow, in contrast with all previous methods used in annular flow.

Figure 5.10

Experimental curves X versus L_D/D , from Cousins and Hewitt (1968), and theoretical curves from best fit of Equation 5.24.

5.4 The Linear Momentum Balance Equation.

Interfacial Friction Factor

Consider the following physical model of upwards annular flow in a vertical column:

- A liquid film exists around the column perimeter with a film thickness $\bar{m}$ and with a liquid flow rate W_{LF} .
- A gas core of diameter $(D - 2\bar{m})$ with a gas flow rate W_G , a liquid droplet flow rate W_{LE} , and with a gas core void fraction α_c .
- A gas-liquid interface, through which there is liquid transfer in the form of droplets with a mass flux of deposition onto the liquid film, N_D , and of entrainment from the liquid, N_E . It will be assumed that there exists equilibrium, i.e., $N_E = N_D$.

All the physical quantities represent time average values. In particular, consider the control volume, CV_C , of length L_D and an area equal to the cross section of the the gas core as is sketched in Figure 5.11.

Applying Newton's law and the Reynolds' Transport Theorem over the gas core region, CV_C , enclosed by the area, CS_C , results in the following equation of conservation of linear momentum.:

$$\iint_{CS_C} \underline{T} dA + \iiint_{CV_C} \underline{B} \rho dV = \iint_{CS_C} \underline{v}(\rho \underline{v} \cdot d\underline{A}) + \frac{\partial}{\partial t} \iiint_{CV_C} \underline{v} \rho dV, \quad (5.35)$$

where: $\underline{v}$ is the velocity vector; ρ is the local density; $d\underline{A}$ is an infinitesimal area element vector directed to the exterior of the closed surface, CS_C ; $\underline{B}$ is the local body force vector; and $\underline{T}$ is the local traction vector acting on the surface CS_C .

Figure 5.11

Control volume description for momentum balance in annular flow.

From this vectorial equation, the one of particular interest, is the scalar component on the axial direction, z , which can be obtained by taking the inner product of Equation 5.35 with the unit-directional vector $\underline{k}$ in the z direction. Each term of the resulting scalar equation will be analyzed individually, and approximate expressions will be developed.

The process will be assumed to be stationary in time, i.e., the time average value of the local physical quantities is constant, resulting in:

$$\frac{\partial}{\partial t} \iiint_{CV_G} \underline{k} \cdot \underline{v} \rho dV = 0 . \quad (5.36)$$

For the body force term, only the gravity force will be considered to be present, that is:

$$\underline{B} = -g \underline{k} , \quad (5.37)$$

where g is the acceleration of gravity. Furthermore, the control volume, CV_C , can be partitioned into two regions, CV_{CL} and CV_{CG} , for the liquid and the gas, respectively. Therefore:

$$\iiint_{CV_C} \underline{k} \cdot \underline{B} \rho dV = \iiint_{CV_{CL}} \underline{k} \cdot (-g \underline{k}) \rho_l dV + \iiint_{CV_{CG}} \underline{k} \cdot (-g \underline{k}) \rho_g dV . \quad (5.38)$$

Assuming the gas flow to be incompressible, Equation 5.38 transforms into:

$$\iiint_{CV_C} \underline{k} \cdot \underline{B} \rho dV = -g \left[\rho_l \iiint_{CV_{CL}} dV + \rho_g \iiint_{CV_{CG}} dV \right] . \quad (5.39)$$

Representing the volume of each phase as a fraction of the total volume, using the gas core void fraction, α_c , results in:

$$\iiint_{CV_C} \underline{k} \cdot \underline{B} \rho dV = -g \left[(1 - \alpha_c) \rho_l + \alpha_c \rho_g \right] \frac{\pi D_c^2}{4} L_D . \quad (5.40)$$

The surface forces term can be split into two parts: one over the lateral control surface, CS_{CL} , and another over the circular ends, CS_{CT} , of the cylindrical control volume. On CS_{CL} a constant interfacial stress, $-\tau_i$, exists, resulting from the flow of the gas across the liquid interface. This interface is moving with a velocity, v_i , on the z -direction. Through the end surfaces, CS_{CT} , the flow is basically parallel, therefore only pressure forces exist. The surface force integral in the z direction is then:

$$\begin{aligned} \iint_{CS_C} \underline{k} \cdot \underline{T} dA &= \iint_{CS_{CL}} \underline{k} \cdot \underline{T} dA + \iint_{CS_{CT}} \underline{k} \cdot \underline{T} dA \\ &= -\tau_i \pi D_c L_D + \Delta p_T \frac{\pi D_c^2}{4}, \end{aligned} \quad (5.41)$$

where, Δp_T is the pressure difference between two axial points separated by a distance L_D .

The convective term can also be split in two: the net momentum flux through the ends and the net momentum flux through the lateral area. The first part has a zero contribution, since steady incompressible flow is assumed. Furthermore, there is no gas flow through the lateral area, therefore:

$$\iint_{CS} \underline{k} \cdot \underline{v} (\rho \underline{v} \cdot d\underline{A}) = \iint_{CS_{CL}} v_z (\rho_l \underline{v} \cdot d\underline{A}). \quad (5.42)$$

This remaining term contains the z -momentum flux contribution of the droplets being deposited and entrained. Assuming, that the droplets deposit with an average velocity, $\bar{v}_z$, and are entrained with the velocity of the moving interface, v_i , then Equation 5.42 can be expressed as:

$$\begin{aligned} \iint_{CS} \underline{k} \cdot \underline{v} (\rho \underline{v} \cdot d\underline{A}) &= (\pi D_c L_D) (N_D \bar{v}_z - N_E v_i) \\ &= (\pi D_c L_D) N_D (\bar{v}_z - v_i), \end{aligned} \quad (5.43)$$

where equilibrium annular flow is assumed, that is, $N_E = N_D$.

Replacing Equations 5.40, 5.41 and 5.43 into Equation 5.35, results after some manipulation in:

$$\frac{\Delta p_T}{L_D} = \frac{4\tau_i}{D_c} + g \left[\alpha_c \rho_g + (1 - \alpha_c) \rho_l \right] + \frac{4}{D_c} N_D (\bar{v}_z - v_i) . \quad (5.44)$$

From this equation, the total pressure gradient $\nabla P_T = \Delta P_T / L_D$, can be thought of as the sum of three different pressure gradient terms:

$$\nabla p_T = \nabla p_I + \nabla p_G + \nabla p_E , \quad (5.45)$$

where the terms represent:

- The interfacial pressure gradient, ∇p_I , which expresses the pressure drop due to the gas-liquid interaction at the film interface, and is defined as:

$$\nabla p_I = \frac{4\tau_i}{D_c} . \quad (5.46)$$

- The gravitational pressure gradient, ∇p_G , defined as:

$$\nabla p_G = g \left[\alpha_c \rho_g + (1 - \alpha_c) \rho_l \right] . \quad (5.47)$$

- The entrainment pressure gradient, ∇p_E , due to the acceleration of liquid drops from a slow moving film to a fast moving droplet, and is defined as:

$$\nabla p_E = \frac{4}{D_c} N_D (\bar{v}_z - v_i) . \quad (5.48)$$

To evaluate the relative importance of each term, experimental data can be used. Data concerning the rates of deposition and droplet velocity was obtained as discussed in Sections 5.3.2 and 4.2.2, respectively. Pressure drop, mean film thickness,

and entrainment rate data were not obtained in this study. However, Zabaras (1985) has collected data on these three quantities in identical equipment and over an identical range of gas and liquid rates, and these are tabulated in Table 5.4. The data appear in Figure 5.12 and in Figure 3.8 of Chapter 3 for the average film thickness.

The value of α_c can be obtained, once W_{LE} and $\bar{v}_z$ are known, through the relationship:

$$W_{LE} = \rho_l(1 - \alpha_c)A_c\bar{v}_z. \quad (5.49)$$

The interfacial velocity, v_i , is computed on the basis of a linear velocity profile in the liquid film with an average liquid velocity, U_{LF} , which predicts that:

$$v_i = 2U_{LF} = \frac{8W_{LF}}{\pi\rho_l(D^2 - D_c^2)} = \frac{8(W_L - W_{LE})}{\pi\rho_l(D^2 - D_c^2)}, \quad (5.50)$$

and, finally, the values of ∇p_I can be computed through Equation 5.45.

In Figure 5.13, the computed values of each pressure gradient term in Equation 5.45 are plotted against Re_{GS} , for increasing values of Re_{LS} , where

$$Re_{GS} = \frac{\rho_g U_{GS} D}{\mu_g} \quad \text{and} \quad Re_{LS} = \frac{\rho_l U_{LS} D}{\mu_l}. \quad (5.51)$$

For the lowest liquid rate, it is observed that the entrainment and gravitational pressure gradient have a negligible contribution on ∇p_T . The pressure gradient results primarily from the friction of the gas core against the wavy liquid surface. As Re_{LS} increases, ∇p_E increases. At the largest experimental value of Re_{LS} , ∇p_E can actually be the dominant term over a range of Re_{GS} . ∇p_G remains always practically constant and negligible.

This behavior gives a possible explanation for the existence of a minimum in the ∇p_T versus Re_{GS} curve. For the lowest gas rate, which is close to the rate of

Table 5.4

Experimental data in vertical upwards two-phase flow in a 50.8 mm column. From Zabaras (1985).

Re_{LS}	U_{GS} (m/s)	ρ_g (Kg/m ³)	Re_{GS}	W_{LE} (Kg/s)	$-\nabla p_T$ (N/m ³)	$\bar{m}$ (mm)
310	11.7	1.24	4.1×10^4	1.25×10^{-5}	453	0.662
310	11.9	1.26	4.2×10^4	3.17×10^{-4}	465	0.682
310	12.5	1.26	4.4×10^4	9.62×10^{-4}	461	0.670
310	13.3	1.27	4.8×10^4	1.30×10^{-3}	432	0.632
310	13.9	1.28	5.0×10^4	1.52×10^{-3}	405	0.593
310	18.1	1.32	6.7×10^4	8.00×10^{-4}	340	0.371
310	18.8	1.33	7.0×10^4	6.14×10^{-4}	317	0.329
310	22.7	1.41	9.1×10^4	2.00×10^{-4}	370	0.232
310	22.5	1.40	8.9×10^4	1.83×10^{-4}	380	0.229
310	25.6	1.48	1.1×10^5	0.0	450	0.220
310	26.9	1.52	1.2×10^5	0.0	510	0.199
310	28.1	1.58	1.3×10^5	0.0	570	0.187
768	10.3	1.24	3.6×10^4	8.00×10^{-4}	641	0.879
768	10.4	1.25	3.7×10^4	9.14×10^{-4}	639	0.873
768	10.9	1.26	3.9×10^4	1.61×10^{-3}	621	0.844
768	13.4	1.29	4.9×10^4	2.99×10^{-3}	561	0.750
768	14.7	1.30	5.4×10^4	2.85×10^{-3}	497	0.658
768	15.9	1.31	5.9×10^4	2.79×10^{-3}	493	0.600
768	18.0	1.35	6.9×10^4	2.26×10^{-3}	448	0.506
768	21.6	1.43	8.7×10^4	5.70×10^{-4}	445	0.390
768	24.3	1.50	1.0×10^5	3.18×10^{-8}	496	0.345
768	25.5	1.55	1.1×10^5	0.0	540	0.335
768	27.3	1.62	1.2×10^5	2.89×10^{-4}	630	0.311

Table 5.4 continuation

Experimental data in vertical upwards two-phase flow in a 50.8 mm column. From Zabaras (1985).

Re_{LS}	U_{GS} (m/s)	ρ_g (Kg/m ³)	Re_{GS}	W_{LE} (Kg/s)	$-\nabla p_T$ (N/m ³)	$\bar{m}$ (mm)
1550	09.5	1.25	3.4×10^4	6.48×10^{-4}	830	1.100
1550	10.3	1.26	3.6×10^4	1.34×10^{-3}	824	1.080
1550	11.1	1.28	4.0×10^4	2.65×10^{-3}	791	1.040
1550	12.6	1.30	4.6×10^4	5.26×10^{-3}	721	0.938
1550	16.5	1.36	6.3×10^4	6.99×10^{-3}	580	0.676
1550	17.2	1.37	6.7×10^4	6.73×10^{-3}	552	0.621
1550	20.9	1.46	8.6×10^4	4.12×10^{-3}	560	0.491
1550	21.3	1.48	8.9×10^4	4.00×10^{-3}	571	0.475
1550	22.8	1.53	9.9×10^4	2.44×10^{-3}	588	0.446
1550	23.8	1.56	1.0×10^5	2.13×10^{-3}	636	0.428
1550	24.6	1.60	1.1×10^5	1.50×10^{-3}	653	0.410
1550	26.2	1.69	1.2×10^5	1.10×10^{-3}	726	0.382
3100	06.8	1.24	2.3×10^4	0.0	1071	1.400
3100	07.4	1.25	2.6×10^4	0.0	1034	1.350
3100	08.3	1.26	3.0×10^4	4.94×10^{-4}	1007	1.300
3100	09.6	1.29	3.5×10^4	3.45×10^{-3}	914	1.180
3100	11.0	1.31	4.1×10^4	6.12×10^{-3}	876	1.120
3100	14.9	1.38	5.8×10^4	1.31×10^{-2}	699	0.860
3100	17.5	1.44	7.1×10^4	1.50×10^{-2}	666	0.747
3100	19.5	1.52	8.3×10^4	1.56×10^{-2}	671	0.677
3100	20.8	1.58	9.3×10^4	1.52×10^{-2}	682	0.641
3100	22.5	1.67	1.1×10^5	1.33×10^{-2}	747	0.597
3100	23.7	1.75	1.2×10^5	1.18×10^{-2}	783	0.573
3100	24.8	1.83	1.3×10^5	1.02×10^{-2}	823	0.550

Figure 5.12

Experimental values of ∇p_T , W_{LE} , versus Re_{GS} , from Zabaraz (1985).

inception of annular flow, the liquid film transports most of the liquid, as can be concluded from Figure 5.12. As the gas rate is increased for a fixed liquid rate, the amount of liquid transported by the film is reduced by an increase in W_{LE} until a maximum in entrainment is achieved. During this process more and more liquid is injected from the film into the gas in the form of droplets, which have a higher specific area per unit volume of liquid. This results in an increase in the efficiency of momentum transfer between gas and drop and a lower pressure drop. This process increases in intensity up to the point where ∇p_T reaches the minimum. Past this minimum, the liquid film becomes thinner as Re_{GS} increases. As this happens W_{LE} decreases with corresponding increase in ∇p_T and decrease of ∇p_E .

This is only a partial explanation. Otherwise, the maximums on ∇p_E and ∇p_T would have to coincide in Re_{GS} , which is not always the case. Certainly, the structure of the liquid film and its relation with Re_{GS} have a certain contribution to the overall behavior.

There exist extensive studies of the interfacial structure in two phase flow. In particular, many correlations have been proposed for the interfacial friction factor, f_i , few with any physical basis. In general, the friction factor is calculated directly from the total measured pressure gradient and empirically correlated. From Figure 5.13, it is clear that only a component of this measured pressure drop is related to the interfacial shear. With the above analysis in hand it is now possible to evaluate f_i using only that component of pressure drop due to shear, ∇p_F . The interfacial friction factor is usually defined by:

$$f_i = \frac{\tau_i}{\frac{1}{2}\rho_g(U_G - U_i)^2} = \frac{(D - 2\bar{m})\nabla p_I}{2\rho_g(U_G - U_i)^2}, \quad (5.52)$$

Figure 5.13

Various pressure gradient terms in Equation 5.45 versus Re_{GS} , for different values of U_{LS} .

Figure 5.13 continuation

Various pressure gradient terms in Equation 5.45 versus Re_{GS} , for different values of U_{LS} .

where, U_G is the average gas velocity in the gas core, given by:

$$U_G = \frac{4W_G}{\pi(D - 2\bar{m})^2} . \quad (5.53)$$

Wallis (1968), Moeck (1970), Hughmark (1973), and Henstock and Hanratty (1974) have all suggested that f_i is uniquely dependent on $\bar{m}/D$. In order to test this idea the experimental data of Figure 5.13 are presented in Figure 5.14. Following the procedure of the above authors, f_i was calculated neglecting the contribution of entrainment to measured pressure gradient. Thus $\nabla p_I = \nabla p_T$ in Equation 5.52. It is evident that the unique relation between f_i and $\bar{m}/D$ does not really exist and there is a significant apparent dependence on liquid rates. These earlier empirical correlations, as well as the presentation in Figure 5.14, ignore the role of momentum transfer of the droplets in determining the pressure drop.

Values of f_i calculated in two ways are now plotted in Figure 5.15-a and b, where:

$$Re_G = \frac{\rho_g(U_G - U_i)D_c}{\mu_g} . \quad (5.54)$$

The values of f_i in 5.15-a were calculated with $\nabla p_I = \nabla p_T$ while in 5.15-b the correct values of ∇p_I determined by difference were used in 5.15-b. It is now clear in Figure 5.15-b that f_i is independent of Re_{LS} , and the dependence on Re_G can be expressed by the following correlation:

$$\log(f_i) = 1.149 \times 10^5 Re_G^{-1} - 5.491 . \quad (5.55)$$

Thus the liquid rate dependence of the non-corrected values of f_i reflect the changes in entrainment and corresponding changes in pressure drop due to acceleration of these drops.

Figure 5.14
Friction factor values, f_i , evaluated without entrainment contribution versus $\bar{m}/D_c$, for different values of Re_{LS} .

Figure 5.15

Friction factor values, f_i , evaluated with and without entrainment contribution versus Re_G , for different values of Re_{LS} .

It is now clear from these results that the problem of pressure drop modelling in annular two phase flow not only depends on the correct prediction of interfacial friction factors, that was shown to be liquid rate independent, but also, on the capability of determining correctly the droplet dynamics and predicting the rates of droplet entrainment, since these terms contribute significantly to the momentum balance (Equation 5.44) as it is clearly illustrated in Figure 5.13.

Chapter 6

Conclusions and Suggestions for Future Work

6.1 Conclusions

A new laser optics technique was developed in this laboratory, that permitted the simultaneous measurement of droplet size and two velocity components in annular flow. The main attributes of the technique are: high precision in the variables measured; high rates of data acquisition making possible a reliable statistical analysis of the data; and small measuring volumes allowing localized measurements and study of radial profiles.

Because data of this type have never before been reported, it was possible to develop new insights into the dynamics of the droplet motion and the droplet-film interactions. The relevant observations obtained directly from the experimental data which can contribute to a better understanding of annular flow are summarized as follows:

- The droplets in annular flow cover a wide spectrum of sizes (100–3000 μm), with a typical average sizes vary around 500 μm . The size distributions are strongly dependent on gas rates and weakly dependent on liquid rates. Increasing the gas rates results in smaller droplets, and vice-versa. The profiles of mean drop size and maximum drop size showed clearly that the droplet size is not controlled in its formation from the liquid film, but by the droplet interaction with the gas core. Unstable drops in the core are subject to break-up.
- Measurements of the axial drop velocity indicated the presence of a considerable slip between gas and droplets. The drop size is such that the droplet dynamics is controlled by particle inertia. The mean droplet velocity increases only slowly with increasing gas rates and is almost independent of liquid rates. Conditional statistical analysis of the droplets axial velocity revealed an unexpected relationship between size and velocity. Larger droplets travel faster than smaller ones. This observation coupled with the droplet size distributions explained the observed weak dependence of mean velocities with gas rates. The lateral velocities showed an almost independence on gas and liquid rates, being constant along the column radius, while the mean axial velocity increases toward the center.
- The simultaneous measurement of two velocity components permitted the determination of the distribution of the angle of the velocity vector with the column axis. It is shown that these distributions can be used to estimate droplet mass transfer coefficients. The measurements of mass transfer coefficients with this technique can be made for the first time without interfering with the flow field as has always been the case with previous techniques. The angular distri-

butions were found to be basically flow rate independent. The average droplet flight angle was found to be around 8.5° corresponding to an average droplet axial flight distance equivalent to seven column diameters which corresponds to an high rate of droplet renewal along the column.

From the rationalization of the experimental results several important conclusions were made, namely:

- An analysis of the maximum droplet size, revealed that the maximum stable droplet size in annular flow is controlled by the action of forces resulting from pressure fluctuation of the turbulent flow of the gas around the droplet. The critical Weber number found based on this criteria was 0.19. The simultaneous analysis of this result, together with results of the stability of gas bubbles in liquids and liquid droplets in non-miscible liquids, disclosed a possible mechanism responsible for the determination of We_c . This is based on the tuning of the natural frequency of particle oscillation to a characteristic frequency of the core turbulence. This mechanism explains the trend of We_c observed for the different situations analyzed, and opens the possibility for the theoretical estimation of We_c in annular flow once the natural modes of oscillation of a viscous droplet are determined.
- The observed independence of the radial velocity distributions with radial position, confirmed that the radial droplet velocity is controlled by the formation process from the liquid film and maintained practically constant along the axial flight. A droplet formation mechanism was proposed based on the liquid wave being undercut by the fast moving gas. This mechanism correctly predicts the order of magnitude of the lateral velocities observed.

- The droplet dynamics equations were developed and it was shown that the velocity predictions from these equations depend strongly on the type of drag coefficient curves used. In a turbulent core the droplet drag coefficient, C_D , depends not only in the particle Reynolds number, Re , but also on the relative turbulence intensity, I_R . The use of drag laws that account for this dependence revealed interesting new situations of multiplicity and stability of droplet terminal velocities. The dynamic simulations also explain the experimentally observed droplet velocity-size relationship. It is now clear that reliable modelling of droplet dynamics in annular flow will be only possible when drag laws are made available developed which account for turbulence.
- The information obtained on droplet velocities and rates of entrainment was used to formulate a momentum balance including droplet exchange. It was shown that droplet entrainment can be responsible for a significant amount of the total pressure drop. The calculated friction factor values, f_i , computed from the friction loss due only to interfacial shear showed an independence on liquid rates. This result contrasts markedly with previous results where entrainment was not taken into account. The f_i values found are solely dependent on gas Reynolds number. Besides this important result, it was also shown that generalized modelling of pressure drops in annular flow requires correct modelling of droplet velocities and entrainment rates.

6.2 Suggestions for future work

The results of this research point clearly to the needed direction of additional

research on annular flow. These problems emerge naturally as research required if a successful strategy of modelling annular flow is the goal to attain. In particular, the following list of problems are considered the most pertinent:

- The droplet dynamics modelling can be refined only when drag curves are available. This can only be obtained through an experimental research program where droplet drag coefficients are measured not only over a wide range of Re , but also of turbulence levels, rates of acceleration and turbulence scales. Once this is available the dynamics equations for droplet motion can be used to develop statistical models to predict the dynamic properties of the droplet.
- Another important problem is the one concerned with the gas velocity profiles and levels of turbulence in the presence of droplets. At present, single phase gas flow equations are used to model the gas core. This work clearly has shown that the levels of turbulence intensity have to be considerably higher than the ones expected for single phase flow. But there is no direct measurement of turbulence intensity as yet and it is important to obtain this information. This experimental research would not only create valuable data for the study of turbulent droplet flows but would level to a better understanding of annular flow itself.
- The problem of the study of the natural frequency modes of oscillation of a viscous droplet emerges as an interesting theoretical project. If the relationship between the natural modes of oscillation of the droplet and characteristic turbulence frequency is found, as was done for gas bubbles, then the empirical We_c found in this work can be theoretically explained and the mechanism will be verified.

— A complete understanding of annular flow will only be possible when the combined analysis of both the continuous and dispersed phases present in annular flow is made. The study of the wave structure of the liquid film is important. In particular, as related to drops, it is important to understand how the initial droplet angle is acquired once the drop is formed. Also important is the role of drops in the process of collision with the film. Of course the modelling of annular flow will be possible only when a satisfactory understanding of the mechanics of the flow of the wavy film and the droplets and their interaction is in hand.

Appendix A

Experimental Results

A.1 Experimental Conditions at Test Section

Table A.1

Exp #	U_{GS} (m/s)	W_G (Kg/s)	Re_{GS}	U_{LS} (m/s)	W_L (Kg/s)	Re_{LS}	r_M (cm)	p (N/m ²)
21	19.5	0.052	7.2×10^4	0.034	0.069	1684	0.0	1.08×10^5
22	17.8	0.047	6.5×10^4	0.034	0.069	1684	0.0	1.08×10^5
23	15.9	0.042	5.8×10^4	0.034	0.069	1684	0.0	1.08×10^5
24	14.0	0.037	5.2×10^4	0.034	0.069	1684	0.0	1.08×10^5
25	14.1	0.038	5.2×10^4	0.121	0.244	5953	0.0	1.12×10^5
26	24.7	0.069	9.5×10^4	0.034	0.069	1684	0.0	1.15×10^5
27	24.5	0.069	9.6×10^4	0.121	0.244	5953	0.0	1.16×10^5
28	24.7	0.069	9.6×10^4	0.069	0.139	3308	0.0	1.15×10^5
29	21.5	0.060	8.3×10^4	0.121	0.244	5953	0.0	1.14×10^5
30	21.5	0.060	8.2×10^4	0.069	0.139	3308	0.0	1.14×10^5
31	21.6	0.060	8.2×10^4	0.034	0.069	1684	0.0	1.14×10^5
32	17.1	0.046	6.4×10^4	0.121	0.244	5953	0.0	1.12×10^5
33	17.5	0.046	6.4×10^4	0.069	0.139	3392	0.0	1.10×10^5
34	14.5	0.038	5.2×10^4	0.069	0.139	3392	0.0	1.08×10^5
40	24.6	0.068	9.4×10^4	0.034	0.069	1725	2.0	1.15×10^5
41	24.4	0.068	9.4×10^4	0.121	0.244	5953	2.0	1.16×10^5
42	24.6	0.069	9.4×10^4	0.121	0.244	6534	1.0	1.16×10^5
43	24.8	0.068	9.4×10^4	0.034	0.069	1725	1.0	1.14×10^5
44	17.7	0.046	6.3×10^4	0.034	0.069	1725	1.0	1.08×10^5
45	17.5	0.046	6.3×10^4	0.121	0.244	6389	1.0	1.10×10^5
46	17.7	0.045	6.3×10^4	0.034	0.069	1888	1.5	1.08×10^5
47	17.5	0.046	6.3×10^4	0.121	0.244	6244	1.5	1.10×10^5

A.2 Probability Density Functions of droplet diameter, velocities, and angle.

EXPERIMENT # 21

FLOW PARAMETERS : UGS = 19.5 M/S RE(GAS) = 0.72E+03
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 621 DROPLETS

AVERAGE DIAMETER = 612.89 +/- 25.47
 MEDIAN DIAMETER = 554.91
 STANDARD DEVIATION = 323.85
 3RD CEN. MOMENT OF DISTR. = 0.344E+03
 4TH CEN. MOMENT OF DISTR. = 0.432E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1992.60

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
47.81	4	0.6465E-04	0.9309E-0
149.44	19	0.3071E-03	0.2045E-0
249.07	46	0.1067E-02	0.8760E-0
348.70	95	0.1535E-02	0.2339E+0
440.33	77	0.1245E-02	0.3639E+0
547.96	86	0.1390E-02	0.4921E+0
647.59	79	0.1277E-02	0.6290E+0
747.22	47	0.7597E-03	0.7300E+0
846.85	38	0.6142E-03	0.7967E+0
946.43	29	0.4687E-03	0.8514E+0
1046.11	23	0.3717E-03	0.8920E+0
1145.74	20	0.3233E-03	0.9270E+0
1245.37	9	0.1455E-03	0.9507E+0
1345.00	10	0.1616E-03	0.9633E+0
1444.63	6	0.9690E-04	0.9704E+0
1544.26	7	0.1131E-03	0.9800E+0
1643.89	2	0.3233E-04	0.9764E+0
1743.52	1	0.1616E-04	0.9931E+0
1843.15	0	0.3233E-04	0.1001E+0
1942.78	0	0.0000E+00	0.1003E+0

EXPERIMENT # 22

FLOW PARAMETERS : UGS = 17.8 M/S RE(GAS) = 0.65E+03
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 579 DROPLETS

AVERAGE DIAMETER = 584.77 +/- 25.72
 MEDIAN DIAMETER = 539.12
 STANDARD DEVIATION = 315.75
 3RD CEN. MOMENT OF DISTR. = 0.311E+03
 4TH CEN. MOMENT OF DISTR. = 0.426E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2125.77

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
53.14	7	0.1137E-03	0.3234E-0
159.43	39	0.6337E-03	0.4018E-0
265.72	74	0.1202E-02	0.1397E+0
372.01	85	0.1381E-02	0.2812E+0
470.30	78	0.1267E-02	0.4214E+0
584.59	83	0.1349E-02	0.5610E+0
690.87	66	0.1072E-02	0.6724E+0
797.16	45	0.7312E-03	0.7879E+0
903.45	28	0.4550E-03	0.8497E+0
1009.74	22	0.3575E-03	0.8916E+0
1116.03	18	0.2925E-03	0.9266E+0
1222.32	12	0.1950E-03	0.9519E+0
1328.60	12	0.1950E-03	0.9729E+0
1434.89	4	0.6500E-04	0.9872E+0
1541.18	1	0.1625E-04	0.9906E+0
1647.47	1	0.1625E-04	0.9932E+0
1753.76	1	0.1625E-04	0.9950E+0
1860.05	0	0.1625E-04	0.9967E+0
1966.33	1	0.0000E+00	0.9967E+0
2072.62	1	0.1625E-04	0.9969E+0

EXPERIMENT # 23

FLOW PARAMETERS : UGS = 15.9 M/S RE(GAS) = 0.58E+03
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 577 DROPLETS

AVERAGE DIAMETER = 731.49 +/- 33.19
 MEDIAN DIAMETER = 661.42
 STANDARD DEVIATION = 406.76
 3RD CEN. MOMENT OF DISTR. = 0.695E+03
 4TH CEN. MOMENT OF DISTR. = 0.114E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2461.80

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
61.54	5	0.7040E-04	0.1704E-0
184.63	34	0.4787E-03	0.3183E-0
307.72	65	0.9152E-03	0.1170E+0
430.81	85	0.1197E-02	0.2527E+0
553.90	60	0.9574E-03	0.3047E+0
676.99	83	0.1169E-02	0.5147E+0
800.08	63	0.8670E-03	0.6466E+0
923.17	37	0.5210E-03	0.7301E+0
1046.26	37	0.5210E-03	0.7929E+0
1169.35	30	0.4234E-03	0.8512E+0
1292.44	28	0.3942E-03	0.9025E+0
1415.53	10	0.1408E-03	0.9359E+0
1538.62	7	0.7854E-04	0.9404E+0
1661.71	8	0.1126E-03	0.9616E+0
1784.80	7	0.9036E-04	0.9751E+0
1907.89	2	0.2816E-04	0.9830E+0
2030.98	1	0.1400E-04	0.9847E+0
2154.07	4	0.5632E-04	0.9892E+0
2277.16	0	0.2816E-04	0.9951E+0
2400.25	0	0.0000E+00	0.9961E+0

EXPERIMENT # 24

FLOW PARAMETERS : UGS = 14.0 M/S RE(GAS) = 0.52E+03
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 554 DROPLETS

AVERAGE DIAMETER = 758.80 +/- 37.74
 MEDIAN DIAMETER = 671.72
 STANDARD DEVIATION = 453.24
 3RD CEN. MOMENT OF DISTR. = 0.113E+03
 4TH CEN. MOMENT OF DISTR. = 0.195E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2475.24

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
61.80	8	0.1167E-03	0.4443E-0
185.64	33	0.4813E-03	0.3945E-0
309.40	61	0.8897E-03	0.1254E+0
433.17	74	0.1079E-02	0.2503E+0
556.93	71	0.1056E-02	0.3819E+0
680.69	69	0.1006E-02	0.5090E+0
804.45	58	0.8459E-03	0.6234E+0
928.21	53	0.7730E-03	0.7250E+0
1051.98	29	0.4230E-03	0.7994E+0
1175.74	22	0.3209E-03	0.8433E+0
1299.50	17	0.2479E-03	0.8700E+0
1423.26	18	0.2625E-03	0.9100E+0
1547.02	9	0.1313E-03	0.9351E+0
1670.79	6	0.8751E-04	0.9472E+0
1794.55	7	0.1021E-03	0.9594E+0
1918.31	3	0.4375E-04	0.9603E+0
2042.07	4	0.5874E-04	0.9747E+0
2165.83	1	0.1450E-04	0.9706E+0
2289.60	9	0.1313E-03	0.9870E+0
2413.36	1	0.1450E-04	0.1001E+0

EXPERIMENT # 25

FLOW PARAMETERS : UGS = 14.1 M/S RC(GAS) = 0.50E+04
 ULS = 0.121 M/S RC(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 563 DROPLETS

AVERAGE DIAMETER = 763.01 +/- 35.09
 MEDIAN DIAMETER = 700.30
 STANDARD DEVIATION = 424.79
 3RD CEN. MOMENT OF DISTR. = 0.696E+08
 4TH CEN. MOMENT OF DISTR. = 0.130E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2501.08

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
62.53	10	0.1420E-03	0.2767E-0
187.58	37	0.5255E-03	0.4506E-0
312.43	55	0.7812E-03	0.1289E+0
437.69	64	0.9090E-03	0.2336E+0
562.74	79	0.1122E-02	0.3636E+0
687.80	60	0.8522E-03	0.4870E+0
812.05	65	0.7202E-03	0.5977E+0
937.90	49	0.6960E-03	0.7015E+0
1062.94	39	0.5539E-03	0.7773E+0
1188.01	37	0.5255E-03	0.8454E+0
1313.06	23	0.3247E-03	0.9004E+0
1438.12	9	0.1270E-03	0.9267E+0
1563.17	12	0.1704E-03	0.9440E+0
1688.23	9	0.1278E-03	0.9649E+0
1813.28	3	0.4261E-04	0.9747E+0
1938.33	2	0.2941E-04	0.9782E+0
2063.39	4	0.5681E-04	0.9838E+0
2188.44	2	0.2941E-04	0.9894E+0
2313.47	2	0.2841E-04	0.9924E+0
2438.53	1	0.1420E-04	0.9959E+0

EXPERIMENT # 26

FLOW PARAMETERS : UGS = 24.7 M/S RC(GAS) = 0.95E+05
 ULS = 0.094 M/S RC(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 676 DROPLETS

AVERAGE DIAMETER = 422.89 +/- 16.51
 MEDIAN DIAMETER = 376.86
 STANDARD DEVIATION = 218.96
 3RD CEN. MOMENT OF DISTR. = 0.164E+08
 4TH CEN. MOMENT OF DISTR. = 0.170E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1865.40

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
46.63	3	0.4758E-04	0.1237E-0
139.90	49	0.7772E-03	0.3716E-0
233.17	134	0.2125E-02	0.1766E+0
326.44	147	0.2331E-02	0.3941E+0
419.71	111	0.1760E-02	0.5870E+0
512.98	83	0.1316E-02	0.7277E+0
606.25	67	0.1043E-02	0.8401E+0
699.52	31	0.4917E-03	0.9124E+0
792.79	20	0.3172E-03	0.9475E+0
886.06	12	0.1903E-03	0.9717E+0
979.33	5	0.7930E-04	0.9834E+0
1072.60	5	0.7930E-04	0.9906E+0
1165.87	2	0.3172E-04	0.9961E+0
1259.14	1	0.1586E-04	0.9977E+0
1352.41	3	0.4758E-04	0.1001E+0
1445.68	0	0.0000E+00	0.1003E+0
1538.95	0	0.0000E+00	0.1003E+0
1632.22	1	0.1586E-04	0.1004E+0
1725.49	1	0.1586E-04	0.1005E+0
1818.76	0	0.0000E+00	0.1006E+0

EXPERIMENT # 27

FLOW PARAMETERS : UGS = 24.5 M/S RC(GAS) = 0.96E+05
 ULS = 0.121 M/S RC(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 585 DROPLETS

AVERAGE DIAMETER = 550.53 +/- 22.85
 MEDIAN DIAMETER = 496.86
 STANDARD DEVIATION = 281.74
 3RD CEN. MOMENT OF DISTR. = 0.247E+08
 4TH CEN. MOMENT OF DISTR. = 0.285E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1902.78

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
49.57	1	0.1724E-04	0.1526E-0
148.71	23	0.3966E-03	0.2160E-0
247.85	63	0.1431E-02	0.1155E+0
346.99	93	0.1604E-02	0.2719E+0
446.12	91	0.1549E-02	0.4287E+0
545.26	85	0.1466E-02	0.5819E+0
644.40	57	0.9028E-03	0.7036E+0
743.54	45	0.7759E-03	0.7893E+0
842.68	32	0.5518E-03	0.8542E+0
941.82	32	0.5510E-03	0.9080E+0
1040.96	18	0.3104E-03	0.9535E+0
1140.10	5	0.8621E-04	0.9709E+0
1239.24	8	0.1379E-03	0.9818E+0
1338.38	2	0.3448E-04	0.9906E+0
1437.51	4	0.6877E-04	0.9951E+0
1536.65	2	0.3448E-04	0.1001E+0
1635.79	2	0.3448E-04	0.1004E+0
1734.93	0	0.0000E+00	0.1006E+0
1834.07	1	0.1724E-04	0.1006E+0
1933.21	0	0.0000E+00	0.1008E+0

EXPERIMENT # 28

FLOW PARAMETERS : UGS = 24.7 M/S RC(GAS) = 0.96E+05
 ULS = 0.069 M/S RC(LIQ) = 0.33E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 590 DROPLETS

AVERAGE DIAMETER = 461.82 +/- 18.22
 MEDIAN DIAMETER = 419.59
 STANDARD DEVIATION = 225.75
 3RD CEN. MOMENT OF DISTR. = 0.140E+08
 4TH CEN. MOMENT OF DISTR. = 0.152E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1663.44

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
41.59	2	0.4076E-04	0.1019E-0
124.76	27	0.5502E-03	0.1865E-0
207.93	51	0.1039E-02	0.8077E-0
291.10	102	0.2079E-02	0.2111E+0
374.27	109	0.2221E-02	0.3705E+0
457.45	78	0.1590E-02	0.5568E+0
540.62	72	0.1467E-02	0.6813E+0
623.79	60	0.1223E-02	0.7956E+0
706.96	37	0.7540E-03	0.8779E+0
790.13	21	0.4279E-03	0.9260E+0
873.30	9	0.1834E-03	0.9509E+0
956.48	3	0.6114E-04	0.9599E+0
1039.65	4	0.8151E-04	0.9656E+0
1122.82	3	0.6114E-04	0.9715E+0
1205.99	5	0.1019E-03	0.9783E+0
1289.16	2	0.4076E-04	0.9849E+0
1372.34	0	0.0000E+00	0.9856E+0
1455.51	4	0.8151E-04	0.9893E+0
1538.68	0	0.0000E+00	0.9933E+0
1621.85	0	0.0000E+00	0.9915E+0

EXPERIMENT # 29

FLOW PARAMETERS : UG5 = 21.5 M/S RE(GAS) = 0.83E+05
 UL5 = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION
 SAMPLE SIZE : 585 DROPLETS

AVERAGE DIAMETER = 635.62 +/- 25.11
 MEDIAN DIAMETER = 579.59
 STANDARD DEVIATION = 309.83
 3RD CEN. MOMENT OF DISTR. = 0.302E+08
 4TH CEN. MOMENT OF DISTR. = 0.396E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1862.52

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
46.56	2	0.3671E-04	-0.4239E-0
139.69	14	0.2570E-03	0.1270E-0
232.81	34	0.6241E-03	0.3208E-0
325.94	59	0.1083E-02	0.1326E+0
419.07	75	0.1377E-02	0.2471E+0
512.19	91	0.1670E-02	0.3922E+0
605.32	76	0.1395E-02	0.5355E+0
698.44	71	0.1303E-02	0.6647E+0
791.57	27	0.4956E-03	0.7462E+0
884.70	42	0.7709E-03	0.8020E+0
977.82	26	0.4773E-03	0.8631E+0
1070.93	23	0.4222E-03	0.9039E+0
1164.07	11	0.2019E-03	0.9327E+0
1257.20	14	0.2570E-03	0.9534E+0
1350.32	6	0.1101E-03	0.9716E+0
1443.45	3	0.5307E-04	0.9783E+0
1536.58	2	0.3671E-04	0.9825E+0
1629.70	2	0.3671E-04	0.9857E+0
1722.83	3	0.5307E-04	0.9900E+0
1815.95	3	0.5307E-04	0.9954E+0

EXPERIMENT # 30

FLOW PARAMETERS : UG5 = 21.6 M/S RE(GAS) = 0.82E+05
 UL5 = 0.069 M/S RE(LIQ) = 0.33E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION
 SAMPLE SIZE : 588 DROPLETS

AVERAGE DIAMETER = 468.58 +/- 19.21
 MEDIAN DIAMETER = 427.10
 STANDARD DEVIATION = 237.62
 3RD CEN. MOMENT OF DISTR. = 0.138E+08
 4TH CEN. MOMENT OF DISTR. = 0.139E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1595.24

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
39.88	5	0.1066E-03	0.1469E-0
119.64	19	0.4051E-03	0.2493E-0
199.40	64	0.1365E-02	0.9689E-0
279.17	82	0.1748E-02	0.2240E+0
358.93	93	0.1983E-02	0.3741E+0
438.69	86	0.1834E-02	0.5288E+0
518.45	68	0.1450E-02	0.6608E+0
598.21	48	0.1029E-02	0.7584E+0
677.98	37	0.8316E-03	0.8315E+0
757.74	28	0.5970E-03	0.8891E+0
837.50	17	0.3625E-03	0.9267E+0
917.26	13	0.2772E-03	0.9515E+0
997.02	10	0.2132E-03	0.9711E+0
1076.78	6	0.1279E-03	0.9850E+0
1156.55	2	0.4264E-04	0.9912E+0
1236.31	3	0.6397E-04	0.9954E+0
1316.07	1	0.2132E-04	0.9988E+0
1395.83	2	0.4264E-04	0.1001E+0
1475.59	1	0.2132E-04	0.1004E+0
1555.35	0	0.0000E+00	0.1005E+0

EXPERIMENT # 31

FLOW PARAMETERS : UG5 = 21.6 M/S RE(GAS) = 0.82E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION
 SAMPLE SIZE : 576 DROPLETS

AVERAGE DIAMETER = 490.73 +/- 20.46
 MEDIAN DIAMETER = 442.30
 STANDARD DEVIATION = 250.57
 3RD CEN. MOMENT OF DISTR. = 0.175E+08
 4TH CEN. MOMENT OF DISTR. = 0.180E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1595.76

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
39.89	4	0.8704E-04	0.4168E-0
119.68	16	0.3481E-03	0.1843E-0
199.47	47	0.1023E-02	0.7072E-0
279.26	86	0.1871E-02	0.1871E+0
359.05	97	0.2111E-02	0.3532E+0
438.83	69	0.1501E-02	0.4946E+0
518.62	72	0.1567E-02	0.6181E+0
598.41	50	0.1088E-02	0.7255E+0
678.20	43	0.9354E-03	0.8055E+0
757.98	24	0.5222E-03	0.8640E+0
837.77	20	0.4352E-03	0.9001E+0
917.56	17	0.3699E-03	0.9335E+0
997.35	9	0.1958E-03	0.9532E+0
1077.14	9	0.1958E-03	0.9711E+0
1156.92	1	0.2176E-04	0.9796E+0
1236.71	4	0.8704E-04	0.9830E+0
1316.50	3	0.6528E-04	0.9900E+0
1396.29	1	0.2176E-04	0.9931E+0
1476.08	2	0.4352E-04	0.9954E+0
1555.86	1	0.2176E-04	0.9988E+0

EXPERIMENT # 32

FLOW PARAMETERS : UG5 = 17.1 M/S RE(GAS) = 0.64E+05
 UL5 = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION
 SAMPLE SIZE : 580 DROPLETS

AVERAGE DIAMETER = 744.01 +/- 31.17
 MEDIAN DIAMETER = 676.01
 STANDARD DEVIATION = 383.04
 3RD CEN. MOMENT OF DISTR. = 0.353E+08
 4TH CEN. MOMENT OF DISTR. = 0.920E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2486.84

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
62.17	3	0.4160E-04	-0.8672E-0
186.51	32	0.4437E-03	0.2527E-0
310.85	50	0.6930E-03	0.9535E-0
435.20	77	0.1068E-02	0.2044E+0
559.54	93	0.1290E-02	0.3542E+0
683.88	79	0.1095E-02	0.5074E+0
808.22	52	0.7210E-03	0.6160E+0
932.56	67	0.9290E-03	0.7186E+0
1056.91	41	0.5655E-03	0.8155E+0
1181.25	27	0.3744E-03	0.8715E+0
1305.57	18	0.2496E-03	0.9095E+0
1429.93	16	0.2219E-03	0.9393E+0
1554.27	6	0.8320E-04	0.9577E+0
1678.61	8	0.1109E-03	0.9697E+0
1802.96	0	0.0000E+00	0.9760E+0
1927.30	3	0.4160E-04	0.9783E+0
2051.64	3	0.4160E-04	0.9839E+0
2175.98	4	0.5346E-04	0.9902E+0
2300.32	0	0.0000E+00	0.9941E+0
2424.67	0	0.0000E+00	0.9925E+0

EXPERIMENT # 33

FLOW PARAMETERS : UG5 = 17.4 M/S RE(GAS) = 0.64E+05
 UL5 = 0.069 M/S RE(LIQ) = 0.34E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 573 DROPLETS

AVERAGE DIAMETER = 647.23 +/- 27.08
 MEDIAN DIAMETER = 588.24
 STANDARD DEVIATION = 330.76
 3RD CEN. MOMENT OF DISTR. = 0.424E+08
 4TH CEN. MOMENT OF DISTR. = 0.585E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2136.25

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
53.41	4	0.6536E-04	0.7644E-0
160.22	17	0.2778E-03	0.2040E-0
267.03	51	0.8933E-03	0.7920E-0
373.84	81	0.1323E-02	0.1947E+0
480.66	98	0.1601E-02	0.3576E+0
587.47	69	0.1127E-02	0.5019E+0
694.28	82	0.1340E-02	0.6349E+0
801.09	42	0.6862E-03	0.7439E+0
907.91	48	0.7843E-03	0.8210E+0
1014.72	17	0.2778E-03	0.8789E+0
1121.53	22	0.3595E-03	0.9100E+0
1228.34	11	0.1797E-03	0.9404E+0
1335.16	11	0.1797E-03	0.9582E+0
1441.97	7	0.1144E-03	0.9750E+0
1548.78	2	0.3268E-04	0.9821E+0
1655.59	9	0.4902E-04	0.9863E+0
1762.41	1	0.1634E-04	0.9896E+0
1869.22	4	0.6536E-04	0.9940E+0
1976.03	1	0.1634E-04	0.9991E+0
2082.84	1	0.1634E-04	0.9992E+0

EXPERIMENT # 34

FLOW PARAMETERS : UG5 = 14.5 M/S RE(GAS) = 0.52E+05
 UL5 = 0.069 M/S RE(LIQ) = 0.34E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 568 DROPLETS

AVERAGE DIAMETER = 791.20 +/- 31.11
 MEDIAN DIAMETER = 739.26
 STANDARD DEVIATION = 378.30
 3RD CEN. MOMENT OF DISTR. = 0.428E+08
 4TH CEN. MOMENT OF DISTR. = 0.725E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2295.56

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
57.39	4	0.6136E-04	-0.5214E-0
172.17	14	0.2147E-03	0.1471E-0
286.94	26	0.3988E-03	0.4525E-0
401.72	67	0.1028E-02	0.1281E+0
516.50	70	0.1074E-02	0.2535E+0
631.28	69	0.1058E-02	0.3739E+0
746.06	76	0.1166E-02	0.5028E+0
860.83	63	0.9663E-03	0.6273E+0
975.61	49	0.7516E-03	0.7254E+0
1090.39	36	0.5522E-03	0.8000E+0
1205.17	28	0.4295E-03	0.8553E+0
1319.95	23	0.3520E-03	0.9010E+0
1434.72	10	0.1534E-03	0.9300E+0
1549.50	7	0.1074E-03	0.9434E+0
1664.28	9	0.1380E-03	0.9572E+0
1779.06	10	0.1534E-03	0.9746E+0
1893.83	4	0.6136E-04	0.9875E+0
2008.61	1	0.1534E-04	0.9913E+0
2123.39	0	0.0000E+00	0.9920E+0
2238.17	1	0.1534E-04	0.9925E+0

EXPERIMENT # 40

FLOW PARAMETERS : UG5 = 24.6 M/S RE(GAS) = 0.94E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION
 SAMPLE SIZE : 577 DROPLETS

AVERAGE DIAMETER = 589.65 +/- 31.14
 MEDIAN DIAMETER = 516.99
 STANDARD DEVIATION = 381.62
 3RD CEN. MOMENT OF DISTR. = 0.732E+08
 4TH CEN. MOMENT OF DISTR. = 0.113E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2367.65

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
59.19	26	0.3804E-03	-0.1144E-0
177.37	66	0.9662E-03	0.8995E-0
295.94	72	0.1054E-02	0.2080E+0
414.34	95	0.1391E-02	0.3549E+0
532.72	79	0.1157E-02	0.5080E+0
651.10	73	0.1069E-02	0.6409E+0
769.49	41	0.6002E-03	0.7393E+0
887.87	40	0.5056E-03	0.8077E+0
1006.25	23	0.3347E-03	0.8633E+0
1124.63	20	0.2920E-03	0.8992E+0
1243.01	12	0.1757E-03	0.9276E+0
1361.40	7	0.1025E-03	0.9435E+0
1479.78	4	0.5856E-04	0.9525E+0
1598.16	5	0.7320E-04	0.9605E+0
1716.54	2	0.2928E-04	0.9643E+0
1834.93	5	0.7320E-04	0.9724E+0
1953.31	3	0.4392E-04	0.9787E+0
2071.69	0	0.0000E+00	0.9859E+0
2190.07	3	0.4392E-04	0.9852E+0
2308.46	1	0.1464E-04	0.9852E+0

EXPERIMENT # 41

FLOW PARAMETERS : UG5 = 24.4 M/S RE(GAS) = 0.95E+05
 UL5 = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION
 SAMPLE SIZE : 538 DROPLETS

AVERAGE DIAMETER = 545.80 +/- 28.74
 MEDIAN DIAMETER = 467.91
 STANDARD DEVIATION = 340.17
 3RD CEN. MOMENT OF DISTR. = 0.432E+08
 4TH CEN. MOMENT OF DISTR. = 0.546E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2555.88

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
63.90	26	0.3702E-03	0.2085E-0
191.69	70	0.1018E-02	0.1059E+0
319.48	109	0.1585E-02	0.2700E+0
447.28	94	0.1396E-02	0.4764E+0
575.07	63	0.9163E-03	0.6204E+0
702.87	63	0.9163E-03	0.7384E+0
830.66	28	0.4073E-03	0.8239E+0
958.45	27	0.3927E-03	0.8709E+0
1086.25	21	0.3054E-03	0.9177E+0
1214.04	11	0.1600E-03	0.9470E+0
1341.84	7	0.1018E-03	0.9625E+0
1469.63	8	0.1146E-03	0.9765E+0
1597.42	5	0.7272E-04	0.9891E+0
1725.22	2	0.2909E-04	0.9953E+0
1853.01	1	0.1454E-04	0.9980E+0
1980.81	0	0.0000E+00	0.9988E+0
2108.60	0	0.0000E+00	0.9987E+0
2236.39	0	0.0000E+00	0.9989E+0
2364.19	0	0.0000E+00	0.9987E+0
2491.98	0	0.0000E+00	0.9988E+0

EXPERIMENT # 42

FLOW PARAMETERS : UG5 = 24.6 M/S RE(GAS) = 0.94E+05
 UL5 = 0.121 M/S RE(LIQ) = 0.65E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION
 SAMPLE SIZE : 590 DROPLETS

AVERAGE DIAMETER = 583.96 +/- 23.23
 MEDIAN DIAMETER = 533.87
 STANDARD DEVIATION = 287.86
 3RD CEN. MOMENT OF DISTR. = 0.218E+08
 4TH CEN. MOMENT OF DISTR. = 0.273E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2089.32

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
52.23	3	0.4867E-04	-0.9222E-0
156.70	31	0.5030E-03	0.2348E-0
261.16	56	0.9006E-03	0.9417E-0
365.63	98	0.1390E-02	0.2270E+0
470.10	97	0.1374E-02	0.3970E+0
574.56	86	0.1395E-02	0.5333E+0
679.03	62	0.1006E-02	0.6788E+0
783.49	51	0.8273E-03	0.7730E+0
887.94	38	0.6165E-03	0.8499E+0
992.43	21	0.3407E-03	0.8982E+0
1096.89	21	0.3407E-03	0.9337E+0
1201.36	8	0.1298E-03	0.9586E+0
1305.82	8	0.1298E-03	0.9710E+0
1410.29	4	0.6490E-04	0.9816E+0
1514.75	3	0.4867E-04	0.9873E+0
1619.22	0	0.0000E+00	0.9898E+0
1723.69	1	0.1622E-04	0.9903E+0
1828.15	1	0.1622E-04	0.9923E+0
1932.62	0	0.0000E+00	0.9931E+0
2037.08	0	0.0000E+00	0.9929E+0

EXPERIMENT # 43

FLOW PARAMETERS : UG5 = 24.8 M/S RE(GAS) = 0.94E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION
 SAMPLE SIZE : 587 DROPLETS

AVERAGE DIAMETER = 494.30 +/- 17.89
 MEDIAN DIAMETER = 455.91
 STANDARD DEVIATION = 221.12
 3RD CEN. MOMENT OF DISTR. = 0.114E+08
 4TH CEN. MOMENT OF DISTR. = 0.116E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1867.58

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
46.69	0	0.0000E+00	0.3118E-0
140.07	22	0.4014E-03	0.1408E-0
233.45	63	0.1149E-02	0.8406E-0
326.83	103	0.1879E-02	0.2289E+0
420.21	119	0.2171E-02	0.4242E+0
513.58	90	0.1642E-02	0.6052E+0
606.96	67	0.1222E-02	0.7374E+0
700.34	47	0.0575E-03	0.8339E+0
793.72	34	0.6203E-03	0.9024E+0
887.10	20	0.3649E-03	0.9485E+0
980.48	9	0.1642E-03	0.9724E+0
1073.86	4	0.7297E-04	0.9829E+0
1167.24	2	0.3649E-04	0.9874E+0
1260.62	3	0.5473E-04	0.9919E+0
1353.99	0	0.0000E+00	0.9944E+0
1447.37	2	0.3649E-04	0.9958E+0
1540.75	1	0.1824E-04	0.9980E+0
1634.13	0	0.0000E+00	0.9995E+0
1727.51	0	0.0000E+00	0.9994E+0
1820.89	0	0.0000E+00	0.9995E+0

EXPERIMENT # 44

FLOW PARAMETERS : UGS = 17.7 M/S RE(GAS) = 0.63E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 577 DROPLETS

AVERAGE DIAMETER = 676.12 +/- 28.54
 MEDIAN DIAMETER = 601.57
 STANDARD DEVIATION = 349.81
 3RD CEN. MOMENT OF DISTR. = 0.471E+08
 4TH CEN. MOMENT OF DISTR. = 0.702E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2364.56

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
59.11	2	0.2932E-04	0.1197E-0
177.34	26	0.3811E-03	0.2521E-0
295.57	72	0.1055E-02	0.1148E+0
413.80	79	0.1143E-02	0.2449E+0
532.03	104	0.1525E-02	0.4060E+0
650.25	68	0.9968E-03	0.3396E+0
768.48	58	0.8502E-03	0.6629E+0
886.71	60	0.8795E-03	0.7478E+0
1004.94	35	0.5131E-03	0.6517E+0
1123.16	23	0.3372E-03	0.8992E+0
1241.39	19	0.2785E-03	0.9339E+0
1359.62	10	0.1466E-03	0.9614E+0
1477.85	5	0.7329E-04	0.9729E+0
1596.08	8	0.1173E-03	0.9847E+0
1714.30	1	0.1466E-04	0.9925E+0
1832.53	4	0.3364E-04	0.9963E+0
1950.76	1	0.1466E-04	0.1001E+0
2068.99	0	0.0000E+00	0.1002E+0
2187.21	1	0.1466E-04	0.1002E+0
2305.44	1	0.1466E-04	0.1004E+0

EXPERIMENT # 45

FLOW PARAMETERS : UGS = 17.5 M/S RE(GAS) = 0.63E+05
 ULS = 0.121 M/S RE(LIQ) = 0.64E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 547 DROPLETS

AVERAGE DIAMETER = 900.67 +/- 34.94
 MEDIAN DIAMETER = 830.97
 STANDARD DEVIATION = 414.94
 3RD CEN. MOMENT OF DISTR. = 0.442E+08
 4TH CEN. MOMENT OF DISTR. = 0.885E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2400.60

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
60.01	0	0.0000E+00	-0.2455E-0
180.04	12	0.1828E-03	0.7970E-0
300.07	24	0.3655E-03	0.4042E-0
420.10	44	0.6702E-03	0.1003E+0
540.13	70	0.1066E-02	0.2077E+0
660.16	63	0.9595E-03	0.3311E+0
780.19	65	0.9900E-03	0.4406E+0
900.22	49	0.7468E-03	0.5529E+0
1020.25	51	0.7768E-03	0.6433E+0
1140.28	39	0.5940E-03	0.7277E+0
1260.31	32	0.4874E-03	0.7893E+0
1380.34	39	0.5940E-03	0.8567E+0
1500.37	16	0.2437E-03	0.9076E+0
1620.40	17	0.2589E-03	0.9354E+0
1740.43	10	0.1523E-03	0.9618E+0
1860.46	4	0.6092E-04	0.9732E+0
1980.49	6	0.9138E-04	0.9822E+0
2100.52	3	0.4549E-04	0.9909E+0
2220.55	2	0.3046E-04	0.9951E+0
2340.58	0	0.0000E+00	0.9976E+0

EXPERIMENT # 46

FLOW PARAMETERS : UGS = 17.7 M/S RE(GAS) = 0.62E+05
 ULS = 0.034 M/S RE(LIQ) = 0.19E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 530 DROPLETS

AVERAGE DIAMETER = 864.63 +/- 41.76
 MEDIAN DIAMETER = 773.52
 STANDARD DEVIATION = 490.54
 3RD CEN. MOMENT OF DISTR. = 0.974E+08
 4TH CEN. MOMENT OF DISTR. = 0.188E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2353.74

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
59.84	4	0.6413E-04	0.1339E-0
176.53	19	0.3046E-03	0.2565E-0
294.22	52	0.8337E-03	0.9641E-0
411.90	50	0.8016E-03	0.1950E+0
529.59	56	0.8978E-03	0.2946E+0
647.28	52	0.8337E-03	0.3967E+0
764.96	55	0.8818E-03	0.4986E+0
882.65	41	0.6573E-03	0.5996E+0
1000.34	41	0.6573E-03	0.6577E+0
1118.02	33	0.5291E-03	0.7373E+0
1235.71	24	0.3848E-03	0.7897E+0
1353.40	27	0.4329E-03	0.8366E+0
1471.08	24	0.3848E-03	0.8872E+0
1588.77	8	0.1283E-03	0.9165E+0
1706.46	13	0.2064E-03	0.9349E+0
1824.15	3	0.1283E-03	0.9542E+0
1941.83	4	0.6413E-04	0.9671E+0
2059.52	2	0.3206E-04	0.9716E+0
2177.21	10	0.1603E-03	0.9824E+0
2294.89	6	0.9619E-04	0.1002E+0

EXPERIMENT # 47

FLOW PARAMETERS : UGS = 17.5 M/S RE(GAS) = 0.62E+05
 ULS = 0.121 M/S RE(LIQ) = 0.62E+04

STATISTICAL ANALYSIS OF DIAMETER --- NUMBER DISTRIBUTION

SAMPLE SIZE : 522 DROPLETS

AVERAGE DIAMETER = 913.59 +/- 40.84
 MEDIAN DIAMETER = 834.23
 STANDARD DEVIATION = 476.07
 3RD CEN. MOMENT OF DISTR. = 0.907E+08
 4TH CEN. MOMENT OF DISTR. = 0.170E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2724.95

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
60.12	6	0.8436E-04	0.5929E-0
180.37	23	0.3234E-03	0.3087E-0
300.62	42	0.5905E-03	0.9532E-0
420.87	46	0.6468E-03	0.1799E+0
540.11	62	0.8718E-03	0.2815E+0
660.36	74	0.1040E-02	0.4152E+0
780.61	61	0.8577E-03	0.5465E+0
900.86	48	0.6749E-03	0.6513E+0
1021.10	35	0.4921E-03	0.7274E+0
1141.35	44	0.6187E-03	0.8057E+0
1261.60	14	0.1968E-03	0.8620E+0
1381.84	19	0.2671E-03	0.8900E+0
1502.09	14	0.1960E-03	0.9233E+0
1622.34	13	0.1823E-03	0.9488E+0
1742.59	7	0.9842E-04	0.9684E+0
1862.83	5	0.7030E-04	0.9791E+0
1983.08	4	0.5624E-04	0.9878E+0
2103.33	3	0.4218E-04	0.9946E+0
2223.58	1	0.1406E-04	0.9985E+0
2343.82	0	0.0000E+00	0.9991E+0

EXPERIMENT # 21

FLOW PARAMETERS : UGS = 19.5 M/S RE(GAS) = 0.72E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 621 DROPLETS

AVERAGE DIAMETER = 1120.00 +/- 31.55
 MEDIAN DIAMETER = 1109.81
 STANDARD DEVIATION = 401.12
 3RD CEN. MOMENT OF DISTR. = 0.613E+07
 4TH CEN. MOMENT OF DISTR. = 0.595E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1992.60

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
49.81	4	0.4553E-05	0.1134E-0
149.44	19	0.2162E-04	0.1612E-0
249.07	66	0.7512E-04	0.6452E-0
348.70	95	0.1081E-03	0.1533E-0
448.33	77	0.2804E-03	0.3283E-0
547.96	86	0.4871E-03	0.6919E-0
647.59	79	0.7064E-03	0.1322E+0
747.22	47	0.6613E-03	0.2026E+0
846.05	38	0.7076E-03	0.2734E+0
946.43	29	0.0456E-03	0.3561E+0
1046.11	23	0.0843E-03	0.4404E+0
1145.74	20	0.1033E-02	0.5398E+0
1245.37	7	0.3684E-03	0.6193E+0
1345.00	10	0.8236E-03	0.6889E+0
1444.63	6	0.6100E-03	0.7602E+0
1544.26	7	0.8934E-03	0.8364E+0
1643.07	2	0.3210E-03	0.7006E+0
1743.52	1	0.1923E-03	0.9203E+0
1843.15	2	0.4234E-03	0.9510E+0
1942.78	1	0.2720E-03	0.9919E+0

EXPERIMENT # 22

FLOW PARAMETERS : UGS = 17.8 M/S RE(GAS) = 0.65E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 579 DROPLETS

AVERAGE DIAMETER = 1105.16 +/- 36.38
 MEDIAN DIAMETER = 1069.57
 STANDARD DEVIATION = 446.64
 3RD CEN. MOMENT OF DISTR. = 0.455E+03
 4TH CEN. MOMENT OF DISTR. = 0.113E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2125.77

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
53.14	7	0.1080E-04	0.9295E-0
159.43	39	0.6016E-04	0.4039E-0
265.72	74	0.1142E-03	0.1308E-0
372.01	85	0.1311E-03	0.2612E-0
478.30	78	0.3484E-03	0.4988E-0
584.59	83	0.6402E-03	0.1029E+0
690.07	66	0.8145E-03	0.1813E+0
797.16	45	0.8685E-03	0.2721E+0
903.45	26	0.7929E-03	0.3604E+0
1009.74	22	0.0639E-03	0.4460E+0
1116.03	18	0.7441E-03	0.5451E+0
1222.32	12	0.8330E-03	0.6373E+0
1328.60	12	0.1061E-02	0.7408E+0
1434.89	4	0.4443E-03	0.8250E+0
1541.18	1	0.1342E-03	0.8504E+0
1647.47	1	0.1451E-03	0.8656E+0
1753.76	1	0.2113E-03	0.8951E+0
1860.05	1	0.2638E-03	0.9127E+0
1966.33	0	0.0000E+00	0.9259E+0
2072.62	2	0.7065E-03	0.9471E+0

EXPERIMENT # 23

FLOW PARAMETERS : UGS = 15.9 M/S RE(GAS) = 0.50E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 577 DROPLETS

AVERAGE DIAMETER = 1367.80 +/- 40.78
 MEDIAN DIAMETER = 1306.63
 STANDARD DEVIATION = 499.74
 3RD CEN. MOMENT OF DISTR. = 0.150E+08
 4TH CEN. MOMENT OF DISTR. = 0.139E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2461.80

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
61.54	5	0.5313E-05	0.1942E-0
184.63	34	0.3619E-04	0.2314E-0
307.72	65	0.6906E-04	0.2314E-0
430.81	85	0.9032E-04	0.1877E-0
553.90	68	0.1990E-03	0.3493E-0
676.99	83	0.4516E-03	0.7492E-0
800.08	43	0.5451E-03	0.1308E+0
923.17	37	0.5132E-03	0.2025E+0
1046.26	37	0.7300E-03	0.2787E+0
1169.35	30	0.8097E-03	0.3727E+0
1292.44	20	0.9945E-03	0.4870E+0
1415.53	10	0.4380E-03	0.5315E+0
1538.62	7	0.4197E-03	0.6316E+0
1661.71	8	0.6163E-03	0.6945E+0
1784.80	7	0.6730E-03	0.7796E+0
1907.89	2	0.2316E-03	0.0392E+0
2030.90	1	0.1007E-03	0.6326E+0
2154.07	4	0.7013E-03	0.9054E+0
2277.16	2	0.3974E-03	0.9910E+0
2400.25	0	0.0000E+00	0.9994E+0

EXPERIMENT # 24

FLOW PARAMETERS : UGS = 14.0 M/S RE(GAS) = 0.52E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 554 DROPLETS

AVERAGE DIAMETER = 1564.79 +/- 48.14
 MEDIAN DIAMETER = 1541.06
 STANDARD DEVIATION = 570.16
 3RD CEN. MOMENT OF DISTR. = -0.276E+08
 4TH CEN. MOMENT OF DISTR. = 0.212E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2475.24

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
61.88	8	0.7035E-05	0.6443E-0
185.64	33	0.2902E-04	0.2314E-0
309.40	61	0.5364E-04	0.7936E-0
433.17	74	0.6508E-04	0.1474E-0
556.93	71	0.1820E-03	0.2903E-0
680.69	58	0.3192E-03	0.4072E-0
804.45	49	0.4116E-03	0.1050E+0
928.21	53	0.5901E-03	0.1688E+0
1051.98	29	0.4547E-03	0.2344E+0
1175.74	22	0.4872E-03	0.2915E+0
1299.50	17	0.5127E-03	0.3519E+0
1423.26	18	0.7176E-03	0.4299E+0
1547.02	9	0.4653E-03	0.5050E+0
1670.79	6	0.4116E-03	0.5533E+0
1794.55	7	0.5707E-03	0.6195E+0
1918.31	3	0.2876E-03	0.6709E+0
2042.07	4	0.4749E-03	0.7208E+0
2165.83	1	0.1521E-03	0.7517E+0
2289.60	2	0.1473E-02	0.8461E+0
2413.36	2	0.4151E-03	0.1018E+0

EXPERIMENT # 25

FLOW PARAMETERS : UGS = 14.1 M/S RE(GAS) = 0.50E+04
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 563 DROPLETS

AVERAGE DIAMETER = 1430.94 +/- 44.35
 MEDIAN DIAMETER = 1343.90
 STANDARD DEVIATION = 536.83
 3RD CEN. MOMENT OF DISTR. = 0.350E+08
 4TH CEN. MOMENT OF DISTR. = 0.187E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2501.08

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
62.53	10	0.9727E-05	0.8124E-0
107.58	37	0.3599E-04	0.3310E-0
312.63	55	0.5350E-04	0.9449E-0
457.69	64	0.6225E-04	0.1542E-0
562.74	79	0.2247E-03	0.3335E-0
687.80	60	0.2939E-03	0.4531E-0
812.85	65	0.5360E-03	0.1160E+0
937.90	49	0.6002E-03	0.1896E+0
1062.96	39	0.6030E-03	0.2681E+0
1188.01	37	0.9095E-03	0.3689E+0
1313.06	23	0.7089E-03	0.4802E+0
1438.12	9	0.3901E-03	0.5499E+0
1563.17	12	0.7003E-03	0.6151E+0
1688.23	9	0.6138E-03	0.7039E+0
1813.28	3	0.2578E-03	0.7575E+0
1938.33	2	0.2004E-03	0.7805E+0
2063.39	4	0.5077E-03	0.8268E+0
2188.44	2	0.3132E-03	0.8806E+0
2313.49	2	0.0735E-03	0.9201E+0
2438.55	2	0.4397E-03	0.9743E+0

EXPERIMENT # 26

FLOW PARAMETERS : UGS = 24.7 M/S RE(GAS) = 0.95E+03
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 676 DROPLETS

AVERAGE DIAMETER = 880.12 +/- 34.12
 MEDIAN DIAMETER = 759.45
 STANDARD DEVIATION = 452.67
 3RD CEN. MOMENT OF DISTR. = 0.662E+08
 4TH CEN. MOMENT OF DISTR. = 0.105E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1863.40

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
46.63	3	0.7822E-05	0.3742E-0
139.90	49	0.1278E-03	0.6731E-0
233.17	134	0.3494E-03	0.3076E-0
326.44	147	0.3833E-03	0.6319E-0
419.71	111	0.8526E-03	0.1202E+0
512.98	83	0.1072E-02	0.2099E+0
606.25	67	0.1442E-02	0.3304E+0
699.52	31	0.9934E-03	0.4464E+0
792.79	20	0.9334E-03	0.5931E+0
886.06	12	0.7926E-03	0.6167E+0
979.33	5	0.4354E-03	0.6717E+0
1072.60	5	0.5762E-03	0.7181E+0
1165.87	2	0.3129E-03	0.7628E+0
1259.14	1	0.2060E-03	0.7808E+0
1352.41	3	0.6710E-03	0.8267E+0
1445.68	0	0.0000E+00	0.8625E+0
1538.95	0	0.0000E+00	0.8532E+0
1632.22	1	0.3937E-03	0.8741E+0
1725.49	1	0.5293E-03	0.9191E+0
1818.76	1	0.6232E-03	0.9715E+0

EXPERIMENT # 27

FLOW PARAMETERS : UGS = 24.5 M/S RE(GAS) = 0.96E+03
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 583 DROPLETS

AVERAGE DIAMETER = 1014.55 +/- 33.06
 MEDIAN DIAMETER = 953.49
 STANDARD DEVIATION = 407.91
 3RD CEN. MOMENT OF DISTR. = 0.334E+08
 4TH CEN. MOMENT OF DISTR. = 0.730E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1982.78

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
49.57	1	0.1663E-05	0.2160E-0
148.71	23	0.3835E-04	0.2331E-0
247.85	83	0.1380E-03	0.1183E-0
346.99	93	0.1547E-03	0.2539E-0
446.12	91	0.4308E-03	0.5248E-0
545.26	85	0.7434E-03	0.1126E+0
644.40	57	0.7833E-03	0.1886E+0
743.54	45	0.9563E-03	0.2731E+0
842.68	32	0.9812E-03	0.3700E+0
941.82	32	0.1321E-02	0.4842E+0
1040.96	18	0.1061E-02	0.6101E+0
1140.10	3	0.3775E-03	0.6736E+0
1239.24	8	0.7384E-03	0.7310E+0
1338.38	2	0.2561E-03	0.7808E+0
1437.51	4	0.4154E-03	0.8219E+0
1536.65	2	0.3659E-03	0.8727E+0
1635.79	2	0.4291E-03	0.9337E+0
1734.93	0	0.0000E+00	0.9337E+0
1834.07	1	0.2977E-03	0.9431E+0
1933.21	1	0.3975E-03	0.9862E+0

EXPERIMENT # 28

FLOW PARAMETERS : UGS = 24.7 M/S RE(GAS) = 0.96E+03
 ULS = 0.069 M/S RE(LIQ) = 0.33E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 590 DROPLETS

AVERAGE DIAMETER = 859.17 +/- 30.08
 MEDIAN DIAMETER = 749.67
 STANDARD DEVIATION = 372.80
 3RD CEN. MOMENT OF DISTR. = 0.250E+08
 4TH CEN. MOMENT OF DISTR. = 0.413E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1663.44

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
41.59	2	0.4058E-05	0.7312E-0
124.76	27	0.5478E-04	0.2256E-0
207.93	51	0.1035E-03	0.9149E-0
291.10	102	0.2069E-03	0.2000E-0
374.27	109	0.6350E-03	0.5506E-0
457.45	78	0.8156E-03	0.1157E+0
540.62	72	0.1254E-02	0.2004E+0
623.79	60	0.1546E-02	0.3197E+0
706.96	37	0.1378E-02	0.4437E+0
790.13	21	0.1049E-02	0.5450E+0
873.30	9	0.6391E-03	0.4162E+0
956.48	3	0.2496E-03	0.6500E+0
1039.65	4	0.4464E-03	0.6781E+0
1122.82	3	0.4484E-03	0.7136E+0
1205.99	5	0.9434E-03	0.7727E+0
1289.16	2	0.4342E-03	0.8377E+0
1372.34	0	0.0000E+00	0.8431E+0
1455.51	4	0.1331E-02	0.9031E+0
1538.68	0	0.0000E+00	0.9711E+0
1621.85	1	0.4849E-03	0.9534E+0

EXPERIMENT # 29

FLOW PARAMETERS : UGS = 21.5 M/S RE(GAS) = 0.83E+05
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 585 DROPLETS

AVERAGE DIAMETER = 1100.61 +/- 32.34
 MEDIAN DIAMETER = 1059.70
 STANDARD DEVIATION = 399.09
 3RD CEN. MOMENT OF DISTR. = 0.155E+08
 4TH CEN. MOMENT OF DISTR. = 0.559E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1862.52

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
46.56	2	0.2062E-05	0.3055E-0
139.69	14	0.1443E-04	0.8242E-0
232.81	34	0.3505E-04	0.3249E-0
325.94	59	0.6082E-04	0.7165E-0
419.07	73	0.2270E-03	0.1927E-0
512.19	91	0.4773E-03	0.5279E-0
605.32	76	0.6474E-03	0.1037E+0
698.44	71	0.9329E-03	0.1817E+0
791.57	27	0.5061E-03	0.2463E+0
884.70	42	0.1099E-02	0.3191E+0
977.82	26	0.9649E-03	0.4103E+0
1070.93	23	0.1059E-02	0.5139E+0
1164.07	11	0.6404E-03	0.5912E+0
1257.20	14	0.1058E-02	0.6704E+0
1350.32	6	0.3793E-03	0.7514E+0
1443.45	3	0.3350E-03	0.7905E+0
1536.58	2	0.2742E-03	0.8101E+0
1629.70	2	0.3505E-03	0.8461E+0
1722.83	3	0.5536E-03	0.8872E+0
1815.95	4	0.9133E-03	0.9541E+0

EXPERIMENT # 31

FLOW PARAMETERS : UGS = 21.6 M/S RE(GAS) = 0.82E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 576 DROPLETS

AVERAGE DIAMETER = 880.87 +/- 26.89
 MEDIAN DIAMETER = 854.56
 STANDARD DEVIATION = 329.22
 3RD CEN. MOMENT OF DISTR. = 0.977E+07
 4TH CEN. MOMENT OF DISTR. = 0.273E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1595.76

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
39.89	4	0.6455E-05	0.1120E-0
119.68	16	0.2582E-04	0.1659E-0
199.47	47	0.7584E-04	0.6056E-0
279.26	86	0.1398E-03	0.1313E-0
359.05	97	0.4567E-03	0.3715E-0
438.83	69	0.5599E-03	0.7735E-0
518.62	72	0.9391E-03	0.1371E+0
598.41	30	0.1039E-02	0.2167E+0
678.20	43	0.1222E-02	0.3082E+0
757.98	24	0.9940E-03	0.3971E+0
837.77	20	0.1139E-02	0.4796E+0
917.56	17	0.1228E-02	0.5778E+0
997.35	9	0.8690E-03	0.6591E+0
1077.14	9	0.1057E-02	0.7397E+0
1156.92	1	0.1501E-03	0.7063E+0
1236.71	4	0.7294E-03	0.8161E+0
1316.50	3	0.4148E-03	0.8766E+0
1396.29	1	0.2630E-03	0.9080E+0
1476.08	2	0.4432E-03	0.9410E+0
1555.86	1	0.3824E-03	0.9934E+0

EXPERIMENT # 30

FLOW PARAMETERS : UGS = 21.6 M/S RE(GAS) = 0.82E+05
 ULS = 0.069 M/S RE(LIQ) = 0.03E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 588 DROPLETS

AVERAGE DIAMETER = 850.66 +/- 26.50
 MEDIAN DIAMETER = 810.26
 STANDARD DEVIATION = 327.80
 3RD CEN. MOMENT OF DISTR. = 0.128E+08
 4TH CEN. MOMENT OF DISTR. = 0.283E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1595.24

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
39.88	5	0.8872E-05	0.1932E-0
119.64	19	0.3371E-04	0.2330E-0
199.40	64	0.1136E-03	0.8772E-0
279.17	82	0.1455E-03	0.1799E-0
358.93	93	0.4773E-03	0.4170E-0
438.69	86	0.7594E-03	0.9165E-0
518.45	68	0.9845E-03	0.1620E+0
598.21	48	0.1079E-02	0.2447E+0
677.98	39	0.1219E-02	0.3359E+0
757.74	28	0.1281E-02	0.4375E+0
837.50	17	0.1042E-02	0.5306E+0
917.26	13	0.1010E-02	0.6106E+0
997.02	10	0.1061E-02	0.6940E+0
1076.78	6	0.7913E-03	0.7713E+0
1156.55	2	0.3158E-03	0.8115E+0
1236.31	3	0.6370E-03	0.8501E+0
1316.07	1	0.2289E-03	0.8847E+0
1395.83	2	0.5891E-03	0.9156E+0
1475.59	1	0.3535E-03	0.9564E+0
1555.35	1	0.4241E-03	0.9782E+0

EXPERIMENT # 32

FLOW PARAMETERS : UGS = 17.1 M/S RE(GAS) = 0.64E+05
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 580 DROPLETS

AVERAGE DIAMETER = 1350.85 +/- 41.89
 MEDIAN DIAMETER = 1283.30
 STANDARD DEVIATION = 514.67
 3RD CEN. MOMENT OF DISTR. = 0.413E+08
 4TH CEN. MOMENT OF DISTR. = 0.140E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2486.84

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
62.17	3	0.3246E-05	-0.5704E-0
186.51	32	0.3462E-04	0.2195E-0
310.85	50	0.5409E-04	0.8059E-0
435.20	77	0.8330E-04	0.1538E-0
559.54	93	0.2910E-03	0.3735E-0
683.88	79	0.4360E-03	0.8537E-0
808.22	52	0.4371E-03	0.1361E+0
932.56	47	0.9228E-03	0.2215E+0
1056.91	41	0.7930E-03	0.3324E+0
1181.25	27	0.7454E-03	0.4269E+0
1305.59	18	0.6880E-03	0.5141E+0
1429.93	16	0.7854E-03	0.6097E+0
1554.27	6	0.3722E-03	0.6787E+0
1678.61	0	0.6448E-03	0.7445E+0
1802.96	0	0.0000E+00	0.7845E+0
1927.30	3	0.3797E-03	0.8025E+0
2051.64	3	0.4208E-03	0.8535E+0
2175.98	4	0.6924E-03	0.9267E+0
2300.32	0	0.0000E+00	0.9731E+0
2424.67	1	0.2536E-03	0.9662E+0

EXPERIMENT # 33

FLOW PARAMETERS : UGS = 17.4 M/S RE(GAS) = 0.64C+05
 ULS = 0.069 M/S RE(LIQ) = 0.34E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 573 DROPLETS

AVERAGE DIAMETER = 1175.01 +/- 36.88
 MEDIAN DIAMETER = 1128.06
 STANDARD DEVIATION = 450.40
 3RD CEN. MOMENT OF DISTR. = 0.235E+08
 4TH CEN. MOMENT OF DISTR. = 0.908E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2136.23

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
33.41	4	0.5019E-05	0.1445E-0
160.22	17	0.2133E-04	0.1875E-0
267.03	51	0.6399E-04	0.4940E-0
373.84	81	0.1016E-03	0.1416E-0
480.66	98	0.3488E-03	0.3875E-0
587.47	69	0.4329E-03	0.7875E-0
694.28	82	0.8356E-03	0.1488E+0
801.09	42	0.6951E-03	0.2291E+0
907.91	40	0.1104E-02	0.3284E+0
1014.72	17	0.3433E-03	0.4162E+0
1121.53	22	0.9435E-03	0.4932E+0
1228.34	11	0.6386E-03	0.5308E+0
1335.16	11	0.7892E-03	0.6539E+0
1441.97	7	0.6386E-03	0.7355E+0
1548.78	2	0.2424E-03	0.7788E+0
1655.59	3	0.4329E-03	0.8159E+0
1762.41	1	0.1644E-03	0.8442E+0
1869.22	4	0.8256E-03	0.8977E+0
1976.03	1	0.2572E-03	0.9645E+0
2082.84	1	0.2779E-03	0.9736E+0

EXPERIMENT # 34

FLOW PARAMETERS : UGS = 14.5 M/S RE(GAS) = 0.32E+05
 ULS = 0.069 M/S RE(LIQ) = 0.34E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 568 DROPLETS

AVERAGE DIAMETER = 1295.76 +/- 34.62
 MEDIAN DIAMETER = 1271.01
 STANDARD DEVIATION = 420.99
 3RD CEN. MOMENT OF DISTR. = 0.436E+07
 4TH CEN. MOMENT OF DISTR. = 0.720E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2293.56

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
37.39	4	0.3528E-05	0.8447E-0
172.17	14	0.1235E-04	0.9839E-0
286.94	26	0.2293E-04	0.2906E-0
401.72	67	0.5909E-04	0.7009E-0
516.50	70	0.1764E-03	0.2022E-0
631.28	69	0.3043E-03	0.4707E-0
746.06	76	0.5415E-03	0.9541E-0
860.83	63	0.6923E-03	0.1671E+0
975.61	49	0.7964E-03	0.2530E+0
1090.39	36	0.8220E-03	0.3465E+0
1205.17	28	0.8590E-03	0.4420E+0
1319.95	23	0.9040E-03	0.5461E+0
1434.72	10	0.5203E-03	0.6290E+0
1549.50	7	0.4612E-03	0.6810E+0
1664.28	9	0.7311E-03	0.7468E+0
1779.06	10	0.9913E-03	0.8510E+0
1893.83	4	0.4745E-03	0.9389E+0
2008.61	1	0.1314E-03	0.9703E+0
2123.39	0	0.0000E+00	0.9760E+0
2238.17	1	0.2090E-03	0.9835E+0

EXPERIMENT # 40

FLOW PARAMETERS : UG5 = 24.6 M/S RE(GAS) = 0.94E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 577 DROPLETS

AVERAGE DIAMETER = 1293.55 +/- 43.84
 MEDIAN DIAMETER = 1235.88
 STANDARD DEVIATION = 537.33
 3RD CEN. MOMENT OF DISTR. = 0.815E+07
 4TH CEN. MOMENT OF DISTR. = 0.173E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2367.65

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROD. DIS
59.19	26	0.3894E-04	0.5848E-0
177.57	46	0.9885E-04	0.9435E-0
295.96	72	0.1078E-03	0.2198E-0
414.34	95	0.1423E-03	0.3566E-0
532.72	79	0.3460E-03	0.6300E-0
651.10	73	0.5497E-03	0.1184E+0
769.49	41	0.5197E-03	0.1807E+0
887.87	40	0.7489E-03	0.2366E+0
1006.25	23	0.6246E-03	0.3303E+0
1124.63	20	0.7843E-03	0.4216E+0
1243.01	12	0.5941E-03	0.5053E+0
1361.40	7	0.4957E-03	0.5696E+0
1479.78	4	0.3684E-03	0.6182E+0
1598.16	3	0.5377E-03	0.6745E+0
1716.54	2	0.2696E-03	0.7184E+0
1834.93	5	0.8133E-03	0.7843E+0
1953.31	2	0.3864E-03	0.8566E+0
2071.69	3	0.7024E-03	0.9211E+0
2190.07	0	0.0000E+00	0.9493E+0
2308.46	1	0.3160E-03	0.9613E+0

EXPERIMENT # 41

FLOW PARAMETERS : UG5 = 24.4 M/S RE(GAS) = 0.95E+05
 UL5 = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 538 DROPLETS

AVERAGE DIAMETER = 1084.60 +/- 35.60
 MEDIAN DIAMETER = 1089.52
 STANDARD DEVIATION = 421.25
 3RD CEN. MOMENT OF DISTR. = -0.145E+08
 4TH CEN. MOMENT OF DISTR. = 0.728E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2553.88

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROD. DIS
63.90	26	0.6400E-04	0.4344E-0
191.69	70	0.1723E-03	0.1822E-0
319.48	109	0.2683E-03	0.4786E-0
447.28	96	0.2363E-03	0.7987E-0
575.07	63	0.4406E-03	0.1191E+0
702.87	63	0.7852E-03	0.2017E+0
830.66	28	0.5760E-03	0.2890E+0
958.45	27	0.8640E-03	0.3771E+0
1086.25	21	0.9624E-03	0.4991E+0
1214.04	11	0.6720E-03	0.6047E+0
1341.84	7	0.6080E-03	0.6817E+0
1469.63	8	0.8615E-03	0.7762E+0
1597.42	5	0.7212E-03	0.8825E+0
1725.22	2	0.3741E-03	0.9513E+0
1853.01	1	0.2191E-03	0.9886E+0
1980.81	0	0.0000E+00	0.1002E+0
2108.60	0	0.0000E+00	0.1000E+0
2236.39	0	0.0000E+00	0.1001E+0
2364.19	0	0.0000E+00	0.1001E+0
2491.98	0	0.0000E+00	0.1001E+0

EXPERIMENT # 42

FLOW PARAMETERS : UG5 = 24.6 M/S RE(GAS) = 0.94E+05
 UL5 = 0.121 M/S RE(LIQ) = 0.65E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 590 DROPLETS

AVERAGE DIAMETER = 1031.90 +/- 32.53
 MEDIAN DIAMETER = 985.18
 STANDARD DEVIATION = 403.12
 3RD CEN. MOMENT OF DISTR. = 0.381E+08
 4TH CEN. MOMENT OF DISTR. = 0.811E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2089.32

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROD. DIS
52.23	3	0.4830E-05	0.7020E-0
156.70	31	0.4991E-04	0.2661E-0
261.16	56	0.9016E-04	0.1027E-0
365.63	98	0.1378E-03	0.2168E-0
470.10	97	0.4588E-03	0.5294E-0
574.56	86	0.742E-03	0.1136E+0
679.03	62	0.8082E-03	0.1909E+0
783.49	51	0.1033E-02	0.2867E+0
887.96	38	0.1127E-02	0.4039E+0
992.43	21	0.8710E-03	0.5052E+0
1096.89	21	0.1158E-02	0.6139E+0
1201.36	8	0.5699E-03	0.7048E+0
1305.82	8	0.7302E-03	0.7711E+0
1410.29	4	0.4862E-03	0.8374E+0
1514.75	0	0.4685E-03	0.8883E+0
1619.22	0	0.0000E+00	0.9121E+0
1723.69	1	0.2045E-03	0.9184E+0
1828.13	1	0.2689E-03	0.9474E+0
1932.62	0	0.0000E+00	0.9611E+0
2037.08	1	0.3848E-03	0.9702E+0

EXPERIMENT # 43

FLOW PARAMETERS : UG5 = 24.8 M/S RE(GAS) = 0.94E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 587 DROPLETS

AVERAGE DIAMETER = 851.70 +/- 30.23
 MEDIAN DIAMETER = 777.62
 STANDARD DEVIATION = 373.87
 3RD CEN. MOMENT OF DISTR. = 0.498E+08
 4TH CEN. MOMENT OF DISTR. = 0.680E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 1867.58

DIAMETER CLASS	NO OF DROPLETS	PROB. DENS.	PROD. DIS
46.69	0	0.0000E+00	0.1508E-0
140.07	22	0.5044E-04	0.2399E-0
233.45	63	0.1444E-03	0.1229E-0
326.83	103	0.2361E-03	0.2741E-0
420.21	119	0.7910E-03	0.7439E-0
513.58	90	0.1059E-02	0.1632E+0
606.96	67	0.1240E-02	0.2706E+0
700.34	47	0.1373E-02	0.3932E+0
793.72	34	0.1403E-02	0.5242E+0
887.10	20	0.1169E-02	0.6468E+0
980.48	9	0.7176E-03	0.7347E+0
1073.86	4	0.4402E-03	0.7881E+0
1167.24	2	0.2568E-03	0.8170E+0
1260.62	3	0.4929E-03	0.8551E+0
1353.99	0	0.0000E+00	0.8766E+0
1447.37	2	0.4906E-03	0.8967E+0
1540.75	1	0.2958E-03	0.9392E+0
1634.13	0	0.0000E+00	0.9512E+0
1727.51	0	0.0000E+00	0.9401E+0
1820.89	1	0.5480E-03	0.9682E+0

EXPERIMENT # 44

FLOW PARAMETERS : UG5 = 17.7 M/S RE(GAS) = 0.63E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 377 DROPLETS

AVERAGE DIAMETER = 1253.04 +/- 41.29
 MEDIAN DIAMETER = 1179.75
 STANDARD DEVIATION = 506.08
 3RD CEN. MOMENT OF DISTR. = 0.412E+08
 4TH CEN. MOMENT OF DISTR. = 0.147E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2364.56

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
59 11	2	0.2574E-05	0.2021E-0
177 34	26	0.3347E-04	0.2563E-0
295 57	72	0.9248E-04	0.1105E-0
413 80	78	0.1004E-03	0.2061E-0
532 03	104	0.3807E-03	0.4913E-0
650 25	68	0.4531E-03	0.1007E+0
768 48	58	0.6230E-03	0.1410E+0
886 71	60	0.9034E-03	0.2505E+0
1004 94	35	0.8148E-03	0.3680E+0
1123 16	23	0.7530E-03	0.4577E+0
1241 39	19	0.8320E-03	0.5520E+0
1359 62	10	0.5715E-03	0.6393E+0
1477 85	5	0.3772E-03	0.6803E+0
1596 08	8	0.7749E-03	0.7418E+0
1714 30	1	0.1146E-03	0.8137E+0
1832 53	4	0.5438E-03	0.3490E+0
1950 76	1	0.1789E-03	0.8987E+0
2068 99	0	0.0000E+00	0.9037E+0
2187 21	1	0.2407E-03	0.9154E+0
2305 44	2	0.5767E-03	0.9644E+0

EXPERIMENT # 45

FLOW PARAMETERS : UG5 = 17.5 M/S RE(GAS) = 0.63E+05
 UL5 = 0.121 M/S RE(LIQ) = 0.64E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 347 DROPLETS

AVERAGE DIAMETER = 1401.24 +/- 34.80
 MEDIAN DIAMETER = 1391.12
 STANDARD DEVIATION = 415.27
 3RD CEN. MOMENT OF DISTR. = -0.218E+07
 4TH CEN. MOMENT OF DISTR. = 0.735E+11
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2400.60

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
60 01	0	0.0000E+00	0.1993E-0
180 04	12	0.8457E-05	0.4981E-0
300 07	24	0.1691E-04	0.2229E-0
420 10	44	0.3101E-04	0.4310E-0
540 13	70	0.1466E-03	0.1473E-0
660 16	63	0.2276E-03	0.3494E-0
780 19	45	0.3784E-03	0.7349E-0
900 22	49	0.4574E-03	0.1232E+0
1020 25	51	0.6646E-03	0.1903E+0
1140 28	39	0.7111E-03	0.2753E+0
1260 31	32	0.7808E-03	0.3595E+0
1380 34	39	0.1259E-02	0.4870E+0
1500 37	16	0.6695E-03	0.6054E+0
1620 40	17	0.8689E-03	0.6930E+0
1740 43	10	0.6314E-03	0.7892E+0
1860 46	4	0.3232E-03	0.8415E+0
1980 49	6	0.5539E-03	0.8941E+0
2100 52	3	0.3347E-03	0.9501E+0
2220 55	2	0.2678E-03	0.9845E+0
2340 58	0	0.0000E+00	0.1006E+0

EXPERIMENT # 46

FLOW PARAMETERS : UG5 = 17.7 M/S RE(GAS) = 0.62E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.19E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 330 DROPLETS

AVERAGE DIAMETER = 1586.77 +/- 43.07
 MEDIAN DIAMETER = 1559.65
 STANDARD DEVIATION = 505.88
 3RD CEN. MOMENT OF DISTR. = -0.289E+08
 4TH CEN. MOMENT OF DISTR. = 0.138E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2353.74

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
58 84	4	0.2505E-05	0.7873E-0
176 33	19	0.1190E-04	0.1079E-0
294 22	52	0.3257E-04	0.3991E-0
411 90	50	0.3132E-04	0.7421E-0
529 59	56	0.9894E-04	0.1470E-0
647 28	52	0.1691E-03	0.3025E-0
764 96	55	0.2762E-03	0.5658E-0
882 65	41	0.3389E-03	0.9249E-0
1000 34	41	0.4704E-03	0.1398E+0
1118 02	33	0.5504E-03	0.2015E+0
1235 71	24	0.5149E-03	0.2631E+0
1353 40	27	0.7698E-03	0.3361E+0
1471 08	24	0.8869E-03	0.4406E+0
1588 77	8	0.3746E-03	0.5122E+0
1706 46	10	0.7134E-03	0.5732E+0
1824 15	8	0.5462E-03	0.6519E+0
1941 83	4	0.3407E-03	0.7045E+0
2059 52	2	0.2155E-03	0.7297E+0
2177 21	10	0.1149E-02	0.8068E+0
2294 89	7	0.9840E-03	0.9602E+0

EXPERIMENT # 47

FLOW PARAMETERS : UG5 = 17.5 M/S RE(GAS) = 0.62E+05
 UL5 = 0.121 M/S RE(LIQ) = 0.62E+04

STATISTICAL ANALYSIS OF DIAMETER --- VOLUME DISTRIBUTION

SAMPLE SIZE : 322 DROPLETS

AVERAGE DIAMETER = 1599.45 +/- 45.42
 MEDIAN DIAMETER = 1606.60
 STANDARD DEVIATION = 529.51
 3RD CEN. MOMENT OF DISTR. = -0.362E+07
 4TH CEN. MOMENT OF DISTR. = 0.181E+12
 MINIMUM DIAMETER = 0.00
 MAXIMUM DIAMETER = 2724.95

DIAMETER CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
68 12	6	0.4725E-05	0.6040E-0
204 37	23	0.1811E-04	0.1828E-0
340 62	42	0.3308E-04	0.5613E-0
476 87	46	0.3623E-04	0.9823E-0
613 11	62	0.1418E-03	0.2061E-0
749 36	74	0.3056E-03	0.3148E-0
885 61	61	0.3977E-03	0.9958E-0
1021 86	48	0.4804E-03	0.1610E+0
1158 10	35	0.5001E-03	0.2237E+0
1294 35	44	0.5537E-03	0.3212E+0
1430 60	14	0.3654E-03	0.4045E+0
1566 84	19	0.6733E-03	0.4706E+0
1703 09	14	0.6536E-03	0.5636E+0
1839 34	13	0.7662E-03	0.6613E+0
1975 59	7	0.4985E-03	0.7493E+0
2111 85	5	0.4465E-03	0.8105E+0
2248 08	4	0.4314E-03	0.8711E+0
2384 33	3	0.3835E-03	0.9232E+0
2520 58	1	0.1614E-03	0.9658E+0
2656 82	1	0.1882E-03	0.9835E+0

EXPERIMENT # 21

FLOW PARAMETERS : UGS = 19.5 M/S RE(GAS) = 0.72E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF AXIAL VELOC -- NUMBER DISTRIBUTION
 SAMPLE SIZE : 621 DROPLETS

AVERAGE AXIAL VELOC = 13.79 +/- 0.32
 MEDIAN AXIAL VELOC = 13.69
 STANDARD DEVIATION = 4.10
 3RD CEN. MOMENT OF DISTR. = 0.131E+02
 4TH CEN. MOMENT OF DISTR. = 0.859E+03
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 27.02

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.03	1	0.5960E-03	0.4908E-0
4.05	5	0.2980E-02	0.3724E-0
6.75	42	0.2503E-01	0.4072E-0
9.46	95	0.3662E-01	0.1497E+0
12.16	156	0.9297E-01	0.2533E+0
14.86	161	0.9395E-01	0.6300E+0
17.56	74	0.5402E-01	0.8206E+0
20.26	47	0.2801E-01	0.9305E+0
22.97	12	0.7152E-02	0.9043E+0
25.67	7	0.4172E-02	0.9933E+0

EXPERIMENT # 23

FLOW PARAMETERS : UGS = 15.9 M/S RE(GAS) = 0.50E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF AXIAL VELOC -- NUMBER DISTRIBUTION
 SAMPLE SIZE : 577 DROPLETS

AVERAGE AXIAL VELOC = 12.82 +/- 0.34
 MEDIAN AXIAL VELOC = 12.70
 STANDARD DEVIATION = 4.13
 3RD CEN. MOMENT OF DISTR. = 0.210E+02
 4TH CEN. MOMENT OF DISTR. = 0.916E+03
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 29.04

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.45	1	0.5960E-03	0.7433E-0
4.36	17	0.1015E-01	0.1453E-0
7.26	79	0.4037E-01	0.8947E-0
10.16	135	0.8057E-01	0.3705E+0
13.07	166	0.9907E-01	0.5421E+0
15.97	110	0.6565E-01	0.7886E+0
18.88	54	0.3220E-01	0.7283E+0
21.78	12	0.7162E-02	0.9816E+0
24.68	7	0.4178E-02	0.9941E+0
27.59	1	0.5968E-03	0.1005E+0

EXPERIMENT # 25

FLOW PARAMETERS : UGS = 14.1 M/S RE(GAS) = 0.30E+04
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF AXIAL VELOC -- NUMBER DISTRIBUTION
 SAMPLE SIZE : 563 DROPLETS

AVERAGE AXIAL VELOC = 12.45 +/- 0.36
 MEDIAN AXIAL VELOC = 12.39
 STANDARD DEVIATION = 4.36
 3RD CEN. MOMENT OF DISTR. = 0.362E+02
 4TH CEN. MOMENT OF DISTR. = 0.114E+04
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 29.70

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.48	1	0.5960E-03	0.1621E-0
4.45	24	0.1555E-01	0.2443E-0
7.42	96	0.5741E-01	0.1352E+0
10.39	133	0.7954E-01	0.3399E+0
13.32	125	0.9265E-01	0.6156E+0
16.30	79	0.4725E-01	0.8395E+0
19.30	39	0.2332E-01	0.9259E+0
22.27	15	0.8971E-02	0.9020E+0
25.24	8	0.4704E-02	0.1001E+0
28.21	0	0.0000E+00	0.1011E+0

EXPERIMENT # 22

FLOW PARAMETERS : UGS = 17.8 M/S RE(GAS) = 0.65E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF AXIAL VELOC -- NUMBER DISTRIBUTION
 SAMPLE SIZE : 579 DROPLETS

AVERAGE AXIAL VELOC = 13.45 +/- 0.32
 MEDIAN AXIAL VELOC = 13.19
 STANDARD DEVIATION = 3.98
 3RD CEN. MOMENT OF DISTR. = 0.204E+02
 4TH CEN. MOMENT OF DISTR. = 0.716E+03
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 27.17

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.36	0	0.0000E+00	0.4707E-0
4.08	4	0.2549E-02	0.1002E-0
6.79	40	0.0542E-01	0.3137E-0
9.51	117	0.7437E-01	0.1671E+0
12.23	150	0.7533E-01	0.4065E+0
14.94	132	0.8391E-01	0.6559E+0
17.66	25	0.5402E-01	0.8457E+0
20.38	36	0.2200E-01	0.9481E+0
23.09	11	0.6992E-02	0.9851E+0
25.81	3	0.1907E-02	0.9958E+0

EXPERIMENT # 24

FLOW PARAMETERS : UGS = 14.0 M/S RE(GAS) = 0.52E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF AXIAL VELOC -- NUMBER DISTRIBUTION
 SAMPLE SIZE : 554 DROPLETS

AVERAGE AXIAL VELOC = 11.75 +/- 0.36
 MEDIAN AXIAL VELOC = 11.46
 STANDARD DEVIATION = 4.34
 3RD CEN. MOMENT OF DISTR. = 0.344E+02
 4TH CEN. MOMENT OF DISTR. = 0.111E+04
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 28.14

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.41	3	0.1924E-02	0.1735E-0
4.22	28	0.1796E-01	0.2975E-0
7.03	101	0.6477E-01	0.1473E+0
9.85	135	0.8660E-01	0.3673E+0
12.66	130	0.8339E-01	0.6127E+0
15.48	88	0.5445E-01	0.8118E+0
18.29	49	0.3143E-01	0.9352E+0
21.10	10	0.6415E-02	0.9855E+0
23.92	7	0.4490E-02	0.9963E+0
26.73	2	0.1283E-02	0.1010E+0

EXPERIMENT # 26

FLOW PARAMETERS : UGS = 24.7 M/S RE(GAS) = 0.95E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF AXIAL VELOC -- NUMBER DISTRIBUTION
 SAMPLE SIZE : 676 DROPLETS

AVERAGE AXIAL VELOC = 15.01 +/- 0.33
 MEDIAN AXIAL VELOC = 14.98
 STANDARD DEVIATION = 4.38
 3RD CEN. MOMENT OF DISTR. = 0.134E+02
 4TH CEN. MOMENT OF DISTR. = 0.963E+03
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 28.63

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.43	0	0.0000E+00	0.2939E-0
4.29	4	0.2047E-02	0.2079E-0
7.16	41	0.2110E-01	0.3105E-0
10.02	102	0.5270E-01	0.1348E+0
12.88	149	0.7699E-01	0.3231E+0
15.75	180	0.9300E-01	0.5751E+0
18.61	112	0.5767E-01	0.7961E+0
21.47	37	0.2945E-01	0.9133E+0
24.34	27	0.1295E-01	0.9787E+0
27.20	3	0.1550E-02	0.1001E+0

EXPERIMENT # 27

FLOW PARAMETERS UGS = 24.5 M/S REIGAS) = 0.96E+05
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE 585 DROPLETS

AVERAGE AXIAL VELOC = 15.44 +/- 0.37
 MEDIAN AXIAL VELOC = 15.18
 STANDARD DEVIATION = 4.57
 3RD CEN. MOMENT OF DISTR. = 0.370E+02
 4TH CEN. MOMENT OF DISTR. = 0.145E+04
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 34.21

AXIAL VEL CLASS	NO OF DROPLETS	PROB. DENS.	PROD. DIS
1.71	0	0.0000E+00	-0.4482E-0
5.13	10	0.4997E-02	0.3771E-0
8.55	55	0.2740E-01	0.4965E-0
11.97	152	0.7595E-01	0.2334E+0
15.39	171	0.8545E-01	0.5180E+0
18.82	122	0.6096E-01	0.7750E+0
22.24	52	0.2590E-01	0.9218E+0
25.66	17	0.3495E-02	0.9758E+0
29.08	2	0.1499E-02	0.9909E+0
32.50	0	0.9994E-03	0.9934E+0

EXPERIMENT # 29

FLOW PARAMETERS UGS = 21.5 M/S REIGAS) = 0.83E+05
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE 585 DROPLETS

AVERAGE AXIAL VELOC = 15.21 +/- 0.37
 MEDIAN AXIAL VELOC = 15.09
 STANDARD DEVIATION = 4.52
 3RD CEN. MOMENT OF DISTR. = 0.196E+02
 4TH CEN. MOMENT OF DISTR. = 0.122E+04
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 30.44

AXIAL VEL CLASS	NO OF DROPLETS	PROB. DENS.	PROD. DIS
1.32	1	0.5616E-03	0.1948E-0
4.57	5	0.2808E-02	0.4240E-0
7.61	40	0.2246E-01	0.3671E-0
10.65	107	0.6099E-01	0.1628E+0
13.70	145	0.8140E-01	0.3828E+0
16.74	146	0.8199E-01	0.6393E+0
19.79	88	0.4942E-01	0.8440E+0
22.83	36	0.2022E-01	0.9459E+0
25.87	13	0.7300E-02	0.9844E+0
28.92	3	0.1685E-02	0.9978E+0

EXPERIMENT # 31

FLOW PARAMETERS UGS = 21.6 M/S REIGAS) = 0.82E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE 576 DROPLETS

AVERAGE AXIAL VELOC = 14.33 +/- 0.35
 MEDIAN AXIAL VELOC = 14.11
 STANDARD DEVIATION = 4.31
 3RD CEN. MOMENT OF DISTR. = 0.300E+02
 4TH CEN. MOMENT OF DISTR. = 0.110E+04
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 29.86

AXIAL VEL CLASS	NO OF DROPLETS	PROB. DENS.	PROD. DIS
1.49	0	0.0000E+00	0.5262E-0
4.48	6	0.3489E-02	0.4290E-0
7.46	50	0.2907E-01	0.4809E-0
10.45	116	0.6744E-01	0.1916E+0
13.44	159	0.9245E-01	0.4379E+0
16.42	135	0.7849E-01	0.7022E+0
19.41	73	0.4244E-01	0.8845E+0
22.39	29	0.1337E-01	0.9632E+0
25.38	9	0.5235E-02	0.9849E+0
28.37	4	0.2326E-02	0.9997E+0

EXPERIMENT # 28

FLOW PARAMETERS UGS = 24.7 M/S REIGAS) = 0.96E+05
 ULS = 0.069 M/S RE(LIQ) = 0.33E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE 590 DROPLETS

AVERAGE AXIAL VELOC = 14.90 +/- 0.36
 MEDIAN AXIAL VELOC = 14.80
 STANDARD DEVIATION = 4.44
 3RD CEN. MOMENT OF DISTR. = 0.166E+02
 4TH CEN. MOMENT OF DISTR. = 0.109E+04
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 31.16

AXIAL VEL CLASS	NO OF DROPLETS	PROB. DENS.	PROD. DIS
1.56	0	0.0000E+00	0.4965E-0
4.67	9	0.4895E-02	0.4958E-0
7.79	50	0.2720E-01	0.4908E-0
10.91	120	0.6527E-01	0.1940E+0
14.02	134	0.8377E-01	0.4317E+0
17.14	147	0.7996E-01	0.6963E+0
20.25	71	0.3862E-01	0.8841E+0
23.37	28	0.1523E-01	0.9416E+0
26.49	10	0.5439E-02	0.9920E+0
29.60	0	0.0000E+00	0.1000E+0

EXPERIMENT # 30

FLOW PARAMETERS UGS = 21.6 M/S REIGAS) = 0.82E+05
 ULS = 0.069 M/S RE(LIQ) = 0.33E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE 588 DROPLETS

AVERAGE AXIAL VELOC = 14.49 +/- 0.34
 MEDIAN AXIAL VELOC = 14.33
 STANDARD DEVIATION = 4.26
 3RD CEN. MOMENT OF DISTR. = 0.125E+02
 4TH CEN. MOMENT OF DISTR. = 0.982E+03
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 28.48

AXIAL VEL CLASS	NO OF DROPLETS	PROB. DENS.	PROD. DIS
1.42	0	0.0000E+00	-0.4208E-0
4.27	10	0.5971E-02	0.5016E-0
7.12	32	0.1911E-01	0.3861E-0
9.97	91	0.4434E-01	0.1361E+0
12.82	156	0.9316E-01	0.3523E+0
15.66	146	0.8718E-01	0.6190E+0
18.51	95	0.5673E-01	0.8273E+0
21.36	37	0.3209E-01	0.9366E+0
24.21	17	0.1015E-01	0.9778E+0
27.06	3	0.1791E-02	0.9978E+0

EXPERIMENT # 32

FLOW PARAMETERS UGS = 17.1 M/S REIGAS) = 0.64E+05
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE 580 DROPLETS

AVERAGE AXIAL VELOC = 14.64 +/- 0.37
 MEDIAN AXIAL VELOC = 14.49
 STANDARD DEVIATION = 4.55
 3RD CEN. MOMENT OF DISTR. = 0.170E+02
 4TH CEN. MOMENT OF DISTR. = 0.117E+04
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 28.88

AXIAL VEL CLASS	NO OF DROPLETS	PROB. DENS.	PROD. DIS
1.44	1	0.5970E-03	0.4658E-0
4.33	6	0.3502E-02	0.5867E-0
7.22	44	0.2627E-01	0.4431E-0
10.11	102	0.6089E-01	0.1700E+0
13.00	134	0.8000E-01	0.3798E+0
15.88	133	0.7940E-01	0.6148E+0
18.77	93	0.5552E-01	0.8135E+0
21.66	46	0.2746E-01	0.9320E+0
24.55	16	0.9552E-02	0.9826E+0
27.44	4	0.2330E-02	0.9975E+0

EXPERIMENT # 33

FLOW PARAMETERS : UGS = 17.4 M/S RE(GAS) = 0.64E+05
 UL5 = 0.069 M/S RE(LIQ) = 0.34E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE 573 DROPLETS

AVERAGE AXIAL VELOC = 14.52 +/- 0.35
 MEDIAN AXIAL VELOC = 14.20
 STANDARD DEVIATION = 4.26
 3RD CEN. MOMENT OF DISTR. = 0.196E+02
 4TH CEN. MOMENT OF DISTR. = 0.901E+03
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 20.63

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.53	0	0.0000E+00	0.3244E-0
4.59	7	0.3908E-02	0.4571E-0
7.66	47	0.2678E-01	0.4667E-0
10.72	119	0.6730E-01	0.1874E+0
13.78	178	0.1014E+00	0.4603E+0
16.85	113	0.6430E-01	0.7233E+0
19.91	70	0.3980E-01	0.8776E+0
22.97	33	0.1830E-01	0.9678E+0
26.04	5	0.2849E-02	0.9904E+0
29.10	0	0.0000E+00	0.9986E+0

EXPERIMENT # 34

FLOW PARAMETERS : UGS = 14.5 M/S RE(GAS) = 0.52E+05
 UL5 = 0.069 M/S RE(LIQ) = 0.34E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE 568 DROPLETS

AVERAGE AXIAL VELOC = 14.01 +/- 0.34
 MEDIAN AXIAL VELOC = 13.79
 STANDARD DEVIATION = 4.12
 3RD CEN. MOMENT OF DISTR. = 0.162E+02
 4TH CEN. MOMENT OF DISTR. = 0.829E+03
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 20.67

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.53	0	0.0000E+00	-0.3801E-0
4.60	11	0.6314E-02	0.5258E-0
7.67	50	0.2870E-01	0.5128E-0
10.73	136	0.7807E-01	0.8132E+0
13.80	174	0.9988E-01	0.5014E+0
16.87	111	0.6372E-01	0.7537E+0
19.94	63	0.3616E-01	0.9057E+0
23.00	18	0.1033E-01	0.9752E+0
26.07	4	0.2296E-02	0.9931E+0
29.14	0	0.0000E+00	0.9981E+0

EXPERIMENT # 40

FLOW PARAMETERS : UGS = 24.6 M/S RE(GAS) = 0.94E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE 577 DROPLETS

AVERAGE AXIAL VELOC = 12.29 +/- 0.33
 MEDIAN AXIAL VELOC = 12.06
 STANDARD DEVIATION = 4.08
 3RD CEN. MOMENT OF DISTR. = 0.103E+02
 4TH CEN. MOMENT OF DISTR. = 0.826E+03
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 24.49

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.20	4	0.2831E-02	0.1843E-0
3.67	9	0.6369E-02	0.1747E-0
6.12	53	0.3751E-01	0.7235E-0
8.57	35	0.6015E-01	0.1800E+0
11.02	148	0.1047E+00	0.3962E+0
13.47	116	0.8209E-01	0.6316E+0
15.92	100	0.7077E-01	0.8201E+0
18.37	36	0.2548E-01	0.9399E+0
20.82	17	0.1203E-01	0.9782E+0
23.27	8	0.3661E-02	0.1005E+0

EXPERIMENT # 41

FLOW PARAMETERS : UGS = 24.4 M/S RE(GAS) = 0.93E+05
 UL5 = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE 538 DROPLETS

AVERAGE AXIAL VELOC = 12.59 +/- 0.32
 MEDIAN AXIAL VELOC = 12.48
 STANDARD DEVIATION = 3.77
 3RD CEN. MOMENT OF DISTR. = 0.940E+01
 4TH CEN. MOMENT OF DISTR. = 0.629E+03
 MINIMUM AXIAL VELOC = 0.00
 MAXIMUM AXIAL VELOC = 23.88

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.29	0	0.0000E+00	-0.8754E-0
3.88	11	0.7908E-02	0.7240E-0
6.47	40	0.2873E-01	0.5117E-0
9.06	94	0.6751E-01	0.1710E+0
11.65	150	0.1077E+00	0.4052E+0
14.23	131	0.9409E-01	0.6777E+0
16.82	72	0.5243E-01	0.8600E+0
19.41	30	0.2135E-01	0.9606E+0
22.00	4	0.2873E-02	0.9893E+0
24.59	4	0.2873E-02	0.9916E+0

EXPERIMENT # 42

FLOW PARAMETERS UGS = 24.6 M/S RE(GAS) = 0.94E+03
ULS = 0.121 M/S RE(LIQ) = 0.65E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE : 590 DROPLETS

AVERAGE AXIAL VELOC = 14.22 +/- 0.33
MEDIAN AXIAL VELOC = 14.11
STANDARD DEVIATION = 4.14
3RD CEN. MOMENT OF DISTR. = 0.125E+02
4TH CEN. MOMENT OF DISTR. = 0.849E+03
MINIMUM AXIAL VELOC = 0.00
MAXIMUM AXIAL VELOC = 27.86

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.39	0	0.0000E+00	-0.1675E-0
4.18	7	0.4259E-02	0.3354E-0
6.94	34	0.2046E-01	0.3305E-0
9.75	93	0.3780E-01	0.1397E+0
12.54	149	0.9045E-01	0.2517E+0
15.32	148	0.9004E-01	0.6119E+0
18.11	98	0.5942E-01	0.6251E+0
20.89	39	0.2373E-01	0.9383E+0
23.68	16	0.9734E-02	0.9803E+0
26.47	3	0.1825E-02	0.9982E+0

EXPERIMENT # 44

FLOW PARAMETERS UGS = 17.7 M/S RE(GAS) = 0.63E+03
ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE : 577 DROPLETS

AVERAGE AXIAL VELOC = 12.20 +/- 0.23
MEDIAN AXIAL VELOC = 11.94
STANDARD DEVIATION = 4.05
3RD CEN. MOMENT OF DISTR. = 0.153E+02
4TH CEN. MOMENT OF DISTR. = 0.741E+03
MINIMUM AXIAL VELOC = 0.00
MAXIMUM AXIAL VELOC = 25.59

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.28	2	0.1355E-02	0.7627E-0
3.84	12	0.8127E-02	0.1260E-0
6.40	39	0.3994E-01	0.7060E-0
8.96	117	0.7924E-01	0.2230E+0
11.52	147	0.9954E-01	0.4607E+0
14.07	114	0.7721E-01	0.6930E+0
16.63	72	0.4874E-01	0.8528E+0
19.19	40	0.2709E-01	0.9490E+0
21.75	11	0.7450E-02	0.9921E+0
24.31	2	0.1355E-02	0.9987E+0

EXPERIMENT # 46

FLOW PARAMETERS UGS = 17.7 M/S RE(GAS) = 0.62E+03
ULS = 0.034 M/S RE(LIQ) = 0.19E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE : 520 DROPLETS

AVERAGE AXIAL VELOC = 11.47 +/- 0.25
MEDIAN AXIAL VELOC = 11.27
STANDARD DEVIATION = 4.09
3RD CEN. MOMENT OF DISTR. = 0.148E+02
4TH CEN. MOMENT OF DISTR. = 0.624E+03
MINIMUM AXIAL VELOC = 0.00
MAXIMUM AXIAL VELOC = 25.05

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.25	4	0.3013E-02	-0.1285E-0
3.76	23	0.1732E-01	0.2374E-0
6.24	56	0.4218E-01	0.9431E-0
8.77	112	0.8436E-01	0.2517E+0
11.27	139	0.1047E+00	0.4997E+0
13.78	93	0.7005E-01	0.7228E+0
16.28	64	0.4821E-01	0.8692E+0
18.79	34	0.1308E-01	0.9510E+0
21.29	12	0.9029E-02	0.9814E+0
23.80	2	0.1506E-02	0.9983E+0

EXPERIMENT # 43

FLOW PARAMETERS UGS = 24.8 M/S RE(GAS) = 0.94E+03
ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE : 587 DROPLETS

AVERAGE AXIAL VELOC = 15.45 +/- 0.35
MEDIAN AXIAL VELOC = 15.38
STANDARD DEVIATION = 4.31
3RD CEN. MOMENT OF DISTR. = 0.160E+02
4TH CEN. MOMENT OF DISTR. = 0.908E+03
MINIMUM AXIAL VELOC = 0.00
MAXIMUM AXIAL VELOC = 27.80

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.39	0	0.0000E+00	-0.1816E-0
4.17	0	0.0000E+00	-0.1727E-0
6.95	21	0.1287E-01	0.1011E-0
9.73	80	0.4902E-01	0.9513E-0
12.51	117	0.7170E-01	0.2662E+0
15.29	141	0.8440E-01	0.4883E+0
18.07	126	0.7721E-01	0.7239E+0
20.85	66	0.4044E-01	0.8896E+0
23.63	24	0.1471E-01	0.9416E+0
26.41	11	0.6741E-02	0.9870E+0

EXPERIMENT # 45

FLOW PARAMETERS UGS = 17.5 M/S RE(GAS) = 0.63E+03
ULS = 0.121 M/S RE(LIQ) = 0.64E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE : 547 DROPLETS

AVERAGE AXIAL VELOC = 13.13 +/- 0.32
MEDIAN AXIAL VELOC = 13.13
STANDARD DEVIATION = 3.86
3RD CEN. MOMENT OF DISTR. = 0.380E+01
4TH CEN. MOMENT OF DISTR. = 0.604E+03
MINIMUM AXIAL VELOC = 0.00
MAXIMUM AXIAL VELOC = 27.56

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.38	0	0.0000E+00	0.8850E-0
4.13	7	0.4643E-02	0.6477E-0
6.89	32	0.3447E-01	0.3740E-0
9.65	109	0.6832E-01	0.1992E+0
12.40	145	0.9618E-01	0.4305E+0
15.16	135	0.8955E-01	0.6959E+0
17.91	76	0.5041E-01	0.8924E+0
20.67	23	0.1526E-01	0.9786E+0
23.43	4	0.2653E-02	0.9987E+0
26.18	1	0.6633E-03	0.1003E+0

EXPERIMENT # 47

FLOW PARAMETERS UGS = 17.5 M/S RE(GAS) = 0.62E+03
ULS = 0.121 M/S RE(LIQ) = 0.62E+04

STATISTICAL ANALYSIS OF AXIAL VELOC --- NUMBER DISTRIBUTION

SAMPLE SIZE : 522 DROPLETS

AVERAGE AXIAL VELOC = 12.72 +/- 0.37
MEDIAN AXIAL VELOC = 12.38
STANDARD DEVIATION = 4.33
3RD CEN. MOMENT OF DISTR. = 0.199E+02
4TH CEN. MOMENT OF DISTR. = 0.114E+04
MINIMUM AXIAL VELOC = 0.00
MAXIMUM AXIAL VELOC = 29.10

AXIAL VEL CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.43	6	0.2950E-02	0.1469E-0
4.34	13	0.9375E-02	0.2329E-0
7.27	66	0.4345E-01	0.9896E-0
10.18	125	0.8229E-01	0.2831E+0
13.09	130	0.9875E-01	0.5583E+0
16.00	93	0.6138E-01	0.7936E+0
18.91	42	0.2745E-01	0.9231E+0
21.82	13	0.9875E-02	0.9740E+0
24.73	9	0.5925E-02	0.9940E+0
27.64	0	0.0000E+00	0.1007E+0

EXPERIMENT # 21

FLOW PARAMETERS UGS = 19.5 M/S REIGAS) = 0.70E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 421 DROPLETS

AVERAGE LATERAL VEL = 0.33 1/- 0.23
 MEDIAN LATERAL VEL = 0.34
 STANDARD DEVIATION = 0.30
 3RD CEN. MOMENT OF DISTR. = 0.101E+01
 4TH CEN. MOMENT OF DISTR. = 0.174E+03
 MINIMUM LATERAL VEL = 7.68
 MAXIMUM LATERAL VEL = 7.66

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
-6.89	2	0.210E-02	0.333E-0
-5.36	18	0.109E-01	0.144E-0
-3.03	40	0.304E-01	0.435E-0
-2.30	39	0.235E-01	0.175E+0
-0.77	114	0.110E+00	0.244E+0
0.77	110	0.115E+00	0.323E+0
2.20	124	0.130E+00	0.716E+0
3.33	69	0.602E-01	0.371E+0
5.36	24	0.254E-01	0.943E+0
6.89	18	0.189E-01	0.903E+0

EXPERIMENT # 22

FLOW PARAMETERS UGS = 17.0 M/S REIGAS) = 0.65E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 579 DROPLETS

AVERAGE LATERAL VEL = 0.27 1/- 0.23
 MEDIAN LATERAL VEL = 0.24
 STANDARD DEVIATION = 0.31
 3RD CEN. MOMENT OF DISTR. = 0.940E+00
 4TH CEN. MOMENT OF DISTR. = 0.140E+03
 MINIMUM LATERAL VEL = 7.94
 MAXIMUM LATERAL VEL = 7.94

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
-7.15	1	0.108E-02	0.774E-0
-5.56	16	0.174E-01	0.100E-0
-3.07	30	0.413E-01	0.315E-0
-2.36	95	0.103E+00	0.165E+0
-0.79	121	0.131E+00	0.350E+0
0.79	117	0.127E+00	0.564E+0
2.20	112	0.121E+00	0.760E+0
3.97	45	0.409E-01	0.905E+0
5.56	29	0.215E-01	0.921E+0
7.15	4	0.405E-02	0.100E+0

EXPERIMENT # 23

FLOW PARAMETERS UGS = 15.9 M/S REIGAS) = 0.58E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 577 DROPLETS

AVERAGE LATERAL VEL = 0.39 1/- 0.24
 MEDIAN LATERAL VEL = 0.19
 STANDARD DEVIATION = 0.30
 3RD CEN. MOMENT OF DISTR. = 0.379E+01
 4TH CEN. MOMENT OF DISTR. = 0.187E+03
 MINIMUM LATERAL VEL = 7.08
 MAXIMUM LATERAL VEL = 7.08

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
-7.09	1	0.110E-02	0.918E-0
-5.52	21	0.230E-01	0.137E-0
-3.94	37	0.406E-01	0.612E-0
-2.36	84	0.923E-01	0.161E+0
-0.79	132	0.145E+00	0.356E+0
0.79	103	0.110E+00	0.369E+0
2.36	94	0.103E+00	0.744E+0
3.94	52	0.571E-01	0.872E+0
5.52	32	0.251E-01	0.941E+0
7.09	15	0.165E-01	0.905E+0

EXPERIMENT # 24

FLOW PARAMETERS UGS = 14.0 M/S REIGAS) = 0.52E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 554 DROPLETS

AVERAGE LATERAL VEL = 0.30 1/- 0.22
 MEDIAN LATERAL VEL = 0.33
 STANDARD DEVIATION = 0.26
 3RD CEN. MOMENT OF DISTR. = -0.152E+00
 4TH CEN. MOMENT OF DISTR. = 0.100E+03
 MINIMUM LATERAL VEL = 7.90
 MAXIMUM LATERAL VEL = 7.90

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
-7.11	1	0.114E-02	0.104E-0
-5.53	17	0.194E-01	0.107E-0
-3.94	34	0.382E-01	0.315E-0
-2.37	87	0.993E-01	0.159E+0
-0.79	112	0.128E+00	0.344E+0
0.79	121	0.133E+00	0.559E+0
2.37	107	0.120E+00	0.769E+0
3.95	44	0.502E-01	0.905E+0
5.53	26	0.297E-01	0.962E+0
7.11	4	0.457E-02	0.997E+0

EXPERIMENT # 25

FLOW PARAMETERS UGS = 14.1 M/S REIGAS) = 0.50E+04
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 563 DROPLETS

AVERAGE LATERAL VEL = 0.41 1/- 0.21
 MEDIAN LATERAL VEL = 0.32
 STANDARD DEVIATION = 0.40
 3RD CEN. MOMENT OF DISTR. = 0.248E+01
 4TH CEN. MOMENT OF DISTR. = 0.124E+03
 MINIMUM LATERAL VEL = 7.90
 MAXIMUM LATERAL VEL = 7.90

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
-7.11	0	0.000E+00	0.659E-0
-5.53	11	0.123E-01	0.474E-0
-3.95	29	0.324E-01	0.346E-0
-2.37	90	0.101E+00	0.137E+0
-0.79	120	0.143E+00	0.340E+0
0.79	112	0.125E+00	0.552E+0
2.37	120	0.137E+00	0.777E+0
3.95	34	0.382E-01	0.909E+0
5.53	30	0.373E-01	0.953E+0
7.11	6	0.674E-02	0.100E+0

EXPERIMENT # 26

FLOW PARAMETERS UGS = 24.7 M/S REIGAS) = 0.75E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 676 DROPLETS

AVERAGE LATERAL VEL = -0.61 1/- 0.25
 MEDIAN LATERAL VEL = -0.79
 STANDARD DEVIATION = 0.36
 3RD CEN. MOMENT OF DISTR. = 0.716E+01
 4TH CEN. MOMENT OF DISTR. = 0.272E+03
 MINIMUM LATERAL VEL = 7.52
 MAXIMUM LATERAL VEL = 7.52

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
-6.77	23	0.226E-01	0.704E-0
-5.26	64	0.629E-01	0.710E-0
-3.76	80	0.786E-01	0.177E+0
-2.26	112	0.110E+00	0.318E+0
-0.75	120	0.122E+00	0.501E+0
0.75	83	0.816E-01	0.632E+0
2.26	101	0.993E-01	0.791E+0
3.76	33	0.324E-01	0.892E+0
5.26	39	0.383E-01	0.937E+0
6.77	16	0.157E-01	0.993E+0

EXPERIMENT # 27

FLOW PARAMETERS UGS = 24.5 M/S RC(GAS) = 0.96E+05
ULS = 0.121 M/S RC(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 585 DROPLETS

AVERAGE LATERAL VEL = -1.51 +/- 0.24
MEDIAN LATERAL VEL = -1.70
STANDARD DEVIATION = 3.00
3RD CEN. MOMENT OF DISTR. = 0.937E+01
4TH CEN. MOMENT OF DISTR. = 0.207E+03
MINIMUM LATERAL VEL = -7.65
MAXIMUM LATERAL VEL = 7.65

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-6.88	16	0.1700E-01	-0.3916E-0
-5.35	95	0.1041E+00	0.8344E-0
-3.82	82	0.9141E-01	0.2330E+0
-2.30	113	0.1251E+00	0.3903E+0
-0.77	87	0.1084E+00	0.5828E+0
0.76	84	0.9385E-01	0.7349E+0
2.29	64	0.7150E-01	0.8661E+0
3.82	16	0.1700E-01	0.9323E+0
5.35	14	0.1544E-01	0.9528E+0
6.88	5	0.5586E-02	0.9767E+0

EXPERIMENT # 29

FLOW PARAMETERS UGS = 21.5 M/S RC(GAS) = 0.80E+05
ULS = 0.121 M/S RC(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 585 DROPLETS

AVERAGE LATERAL VEL = -1.55 +/- 0.26
MEDIAN LATERAL VEL = -1.94
STANDARD DEVIATION = 3.26
3RD CEN. MOMENT OF DISTR. = 0.159E+02
4TH CEN. MOMENT OF DISTR. = 0.291E+03
MINIMUM LATERAL VEL = -7.94
MAXIMUM LATERAL VEL = 7.94

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-7.15	18	0.1938E-01	-0.3876E-0
-5.56	95	0.1023E+00	0.8645E-0
-3.97	84	0.9942E-01	0.2359E+0
-2.38	123	0.1324E+00	0.4147E+0
-0.79	87	0.7365E-01	0.6009E+0
0.79	70	0.7535E-01	0.7301E+0
2.39	58	0.6240E-01	0.8406E+0
3.97	25	0.2491E-01	0.9131E+0
5.56	18	0.1938E-01	0.7464E+0
7.15	7	0.7535E-02	0.9723E+0

EXPERIMENT # 31

FLOW PARAMETERS UGS = 21.6 M/S RC(GAS) = 0.82E+05
ULS = 0.034 M/S RC(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 576 DROPLETS

AVERAGE LATERAL VEL = -1.11 +/- 0.26
MEDIAN LATERAL VEL = -1.44
STANDARD DEVIATION = 3.15
3RD CEN. MOMENT OF DISTR. = 0.117E+02
4TH CEN. MOMENT OF DISTR. = 0.234E+03
MINIMUM LATERAL VEL = -8.00
MAXIMUM LATERAL VEL = 8.00

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-7.20	11	0.1194E-01	-0.2479E-0
-5.60	37	0.6195E-01	0.5838E-0
-4.00	95	0.1809E+00	0.1897E+0
-2.40	116	0.1259E+00	0.3750E+0
-0.80	102	0.1107E+00	0.5673E+0
0.80	75	0.8138E-01	0.7205E+0
2.40	47	0.7270E-01	0.8437E+0
4.00	27	0.2930E-01	0.9277E+0
5.60	21	0.2279E-01	0.9460E+0
7.20	6	0.6510E-02	0.9954E+0

EXPERIMENT # 28

FLOW PARAMETERS UGS = 24.7 M/S RC(GAS) = 0.96E+05
ULS = 0.069 M/S RC(LIQ) = 0.33E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 590 DROPLETS

AVERAGE LATERAL VEL = -1.70 +/- 0.24
MEDIAN LATERAL VEL = -2.05
STANDARD DEVIATION = 3.03
3RD CEN. MOMENT OF DISTR. = 0.140E+02
4TH CEN. MOMENT OF DISTR. = 0.236E+03
MINIMUM LATERAL VEL = -8.00
MAXIMUM LATERAL VEL = 8.00

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-7.20	16	0.1675E-01	0.2263E-0
-5.60	75	0.7945E-01	0.7948E-0
-4.00	117	0.1277E+00	0.2469E+0
-2.40	120	0.1271E+00	0.4525E+0
-0.80	100	0.1055E+00	0.6414E+0
0.80	72	0.7627E-01	0.7860E+0
2.40	53	0.5614E-01	0.8937E+0
4.00	15	0.1589E-01	0.9496E+0
5.60	18	0.1707E-01	0.9732E+0
7.20	3	0.3179E-02	0.1000E+0

EXPERIMENT # 30

FLOW PARAMETERS UGS = 21.6 M/S RC(GAS) = 0.82E+05
ULS = 0.069 M/S RC(LIQ) = 0.33E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 580 DROPLETS

AVERAGE LATERAL VEL = -1.24 +/- 0.25
MEDIAN LATERAL VEL = -1.47
STANDARD DEVIATION = 3.07
3RD CEN. MOMENT OF DISTR. = 0.982E+01
4TH CEN. MOMENT OF DISTR. = 0.234E+03
MINIMUM LATERAL VEL = -7.96
MAXIMUM LATERAL VEL = 7.96

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-7.16	11	0.1175E-01	-0.1628E-0
-5.57	69	0.7371E-01	0.6215E-0
-3.98	90	0.9614E-01	0.1974E+0
-2.39	116	0.1239E+00	0.3755E+0
-0.80	101	0.1079E+00	0.5638E+0
0.80	88	0.9401E-01	0.7231E+0
2.39	68	0.7264E-01	0.8596E+0
3.98	24	0.2564E-01	0.9371E+0
5.57	13	0.1387E-01	0.9639E+0
7.16	7	0.7478E-02	0.9841E+0

EXPERIMENT # 32

FLOW PARAMETERS UGS = 17.1 M/S RC(GAS) = 0.64E+05
ULS = 0.121 M/S RC(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 580 DROPLETS

AVERAGE LATERAL VEL = -0.84 +/- 0.25
MEDIAN LATERAL VEL = -1.04
STANDARD DEVIATION = 3.07
3RD CEN. MOMENT OF DISTR. = 0.759E+01
4TH CEN. MOMENT OF DISTR. = 0.217E+03
MINIMUM LATERAL VEL = -7.95
MAXIMUM LATERAL VEL = 7.95

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-7.13	5	0.5422E-02	-0.2382E-0
-5.57	39	0.6398E-01	0.4387E-0
-3.96	75	0.8100E-01	0.1578E+0
-2.39	113	0.1225E+00	0.3206E+0
-0.80	110	0.1193E+00	0.5194E+0
0.79	84	0.9326E-01	0.6877E+0
2.38	71	0.7679E-01	0.8248E+0
3.97	33	0.3570E-01	0.9142E+0
5.56	25	0.2711E-01	0.9600E+0
7.13	3	0.3253E-02	0.9933E+0

EXPERIMENT # 33

FLOW PARAMETERS UGS = 17.4 M/S RE(GAS) = 0.64E+05
ULS = 0.069 M/S RE(LIQ) = 0.34E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION
SAMPLE SIZE : 573 DROPLETS

AVERAGE LATERAL VEL = -0.91 +/- 0.20
MEDIAN LATERAL VEL = -1.30
STANDARD DEVIATION = 3.37
3RD CEN. MOMENT OF DISTR = 0.134E+02
4TH CEN. MOMENT OF DISTR = 0.303E+03
MINIMUM LATERAL VEL = -7.08
MAXIMUM LATERAL VEL = 7.88

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-7.09	12	0.1227E-01	-0.2795E-0
-5.52	69	0.6976E-01	0.6496E-0
-3.94	96	0.1063E+00	0.2066E+0
-2.36	102	0.1130E+00	0.3950E+0
-0.79	77	0.8527E-01	0.3411E+0
0.79	80	0.8859E-01	0.6743E+0
2.36	75	0.8305E-01	0.8162E+0
3.94	28	0.3101E-01	0.9052E+0
5.52	29	0.3211E-01	0.9491E+0
7.09	11	0.1218E-01	0.9933E+0

EXPERIMENT # 34

FLOW PARAMETERS UGS = 14.5 M/S RE(GAS) = 0.52E+05
ULS = 0.069 M/S RE(LIQ) = 0.34E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION
SAMPLE SIZE : 568 DROPLETS

AVERAGE LATERAL VEL = -0.83 +/- 0.27
MEDIAN LATERAL VEL = -1.23
STANDARD DEVIATION = 3.25
3RD CEN. MOMENT OF DISTR = 0.129E+02
4TH CEN. MOMENT OF DISTR = 0.275E+03
MINIMUM LATERAL VEL = -7.85
MAXIMUM LATERAL VEL = 7.85

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-7.06	10	0.1121E-01	-0.9626E-0
-5.49	54	0.6055E-01	0.5321E-0
-3.93	81	0.9083E-01	0.1705E+0
-2.36	117	0.1312E+00	0.3479E+0
-0.79	100	0.1121E+00	0.5476E+0
0.78	69	0.7065E-01	0.6855E+0
2.35	73	0.8186E-01	0.8069E+0
3.92	29	0.3252E-01	0.8937E+0
5.49	31	0.3476E-01	0.9453E+0
7.06	9	0.1009E-01	0.9938E+0

EXPERIMENT # 40

FLOW PARAMETERS UGS = 24.6 M/S RE(GAS) = 0.94E+05
ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION
SAMPLE SIZE : 577 DROPLETS

AVERAGE LATERAL VEL = -0.08 +/- 0.23
MEDIAN LATERAL VEL = -0.27
STANDARD DEVIATION = 2.77
3RD CEN. MOMENT OF DISTR = 0.396E+01
4TH CEN. MOMENT OF DISTR = 0.168E+03
MINIMUM LATERAL VEL = -7.94
MAXIMUM LATERAL VEL = 7.94

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-7.15	4	0.4265E-02	0.3504E-0
-5.56	18	0.1944E-01	0.1972E-0
-3.97	49	0.5340E-01	0.7572E-0
-2.38	97	0.1059E+00	0.1986E+0
-0.79	145	0.1382E+00	0.4175E+0
0.79	106	0.1157E+00	0.6394E+0
2.38	91	0.9922E-01	0.8108E+0
3.97	34	0.3711E-01	0.9200E+0
5.56	25	0.2728E-01	0.9640E+0
7.15	7	0.7640E-02	0.1001E+0

EXPERIMENT # 41

FLOW PARAMETERS UGS = 24.4 M/S RE(GAS) = 0.95E+05
ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION
SAMPLE SIZE : 538 DROPLETS

AVERAGE LATERAL VEL = -0.31 +/- 0.24
MEDIAN LATERAL VEL = -0.32
STANDARD DEVIATION = 2.88
3RD CEN. MOMENT OF DISTR = 0.381E+01
4TH CEN. MOMENT OF DISTR = 0.182E+03
MINIMUM LATERAL VEL = -7.89
MAXIMUM LATERAL VEL = 7.89

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-7.10	4	0.4712E-02	-0.4586E-0
-5.52	29	0.3416E-01	0.2883E-0
-3.95	60	0.7067E-01	0.1111E+0
-2.37	90	0.1060E+00	0.2514E+0
-0.79	102	0.1273E+00	0.4381E+0
0.79	107	0.1260E+00	0.6400E+0
2.37	23	0.3777E-01	0.8226E+0
3.94	33	0.3087E-01	0.9295E+0
5.52	17	0.2002E-01	0.9707E+0
7.10	7	0.3245E-02	0.9946E+0

EXPERIMENT # 42

FLOW PARAMETERS UGS = 24.6 M/S RE(GAS) = 0.94E+05
ULS = 0.121 M/S RE(LIQ) = 0.65E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 590 DROPLETS

AVERAGE LATERAL VEL = -0.53 +/- 0.26
MEDIAN LATERAL VEL = -0.30
STANDARD DEVIATION = 0.21
3RD CEN. MOMENT OF DISTR. = 0.101E+02
4TH CEN. MOMENT OF DISTR. = 0.246E+03
MINIMUM LATERAL VEL = -7.97
MAXIMUM LATERAL VEL = 7.97

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-7.17	7	0.7440E-02	0.4751E-0
-5.58	43	0.4578E-01	0.4146E-0
-3.98	79	0.8400E-01	0.1462E-0
-2.39	103	0.1116E+00	0.3022E+0
-0.80	121	0.1287E+00	0.5006E+0
0.80	81	0.8613E-01	0.6724E+0
2.39	73	0.7973E-01	0.8044E+0
3.98	34	0.3615E-01	0.8974E+0
5.58	34	0.3615E-01	0.9302E+0
7.17	10	0.1043E-01	0.9991E+0

EXPERIMENT # 43

FLOW PARAMETERS UGS = 24.0 M/S RE(GAS) = 0.94E+05
ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 587 DROPLETS

AVERAGE LATERAL VEL = -1.27 +/- 0.25
MEDIAN LATERAL VEL = -1.46
STANDARD DEVIATION = 0.07
3RD CEN. MOMENT OF DISTR. = 0.791E+01
4TH CEN. MOMENT OF DISTR. = 0.228E+03
MINIMUM LATERAL VEL = -7.64
MAXIMUM LATERAL VEL = 7.64

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-6.88	24	0.2676E-01	-0.7416E-0
-5.35	70	0.7804E-01	0.8610E-0
-3.82	79	0.0300E-01	0.2101E+0
-2.29	114	0.1293E+00	0.3783E+0
-0.76	100	0.1115E+00	0.5473E+0
0.76	38	0.9311E-01	0.7264E+0
2.29	42	0.6712E-01	0.8375E+0
3.82	23	0.2787E-01	0.9297E+0
5.35	17	0.1895E-01	0.9622E+0
6.88	6	0.6689E-02	0.9859E+0

EXPERIMENT # 44

FLOW PARAMETERS UGS = 17.7 M/S RE(GAS) = 0.63E+05
ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 577 DROPLETS

AVERAGE LATERAL VEL = -1.12 +/- 0.20
MEDIAN LATERAL VEL = -1.12
STANDARD DEVIATION = 2.49
3RD CEN. MOMENT OF DISTR. = 0.405E+01
4TH CEN. MOMENT OF DISTR. = 0.127E+03
MINIMUM LATERAL VEL = -7.91
MAXIMUM LATERAL VEL = 7.91

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-7.12	3	0.5478E-02	-0.5635E-0
-5.54	38	0.4163E-01	0.3343E-0
-3.95	71	0.7778E-01	0.1261E+0
-2.37	125	0.1369E+00	0.2922E+0
-0.79	167	0.1030E+00	0.3579E+0
0.79	93	0.1041E+00	0.7926E+0
2.37	50	0.5478E-01	0.9126E+0
3.95	16	0.1753E-01	0.9684E+0
5.54	5	0.5478E-02	0.9832E+0
7.12	4	0.4382E-02	0.9915E+0

EXPERIMENT # 45

FLOW PARAMETERS UGS = 17.5 M/S RE(GAS) = 0.63E+05
ULS = 0.121 M/S RE(LIQ) = 0.64E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 547 DROPLETS

AVERAGE LATERAL VEL = -0.87 +/- 0.21
MEDIAN LATERAL VEL = -0.96
STANDARD DEVIATION = 2.55
3RD CEN. MOMENT OF DISTR. = 0.572E+01
4TH CEN. MOMENT OF DISTR. = 0.138E+03
MINIMUM LATERAL VEL = -7.23
MAXIMUM LATERAL VEL = 7.23

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-6.51	10	0.1244E-01	-0.3465E-0
-5.04	38	0.4804E-01	0.4482E-0
-3.62	58	0.7333E-01	0.1306E+0
-2.17	111	0.1403E+00	0.2771E+0
-0.72	166	0.2099E+00	0.5481E+0
0.72	48	0.8597E-01	0.7680E+0
2.17	53	0.6701E-01	0.8689E+0
3.62	21	0.2635E-01	0.9391E+0
5.04	13	0.1896E-01	0.9673E+0
6.51	6	0.7586E-02	0.9921E+0

EXPERIMENT # 46

FLOW PARAMETERS UGS = 17.7 M/S RE(GAS) = 0.62E+05
ULS = 0.034 M/S RE(LIQ) = 0.19E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 330 DROPLETS

AVERAGE LATERAL VEL = 0.26 +/- 0.27
MEDIAN LATERAL VEL = -0.06
STANDARD DEVIATION = 3.21
3RD CEN. MOMENT OF DISTR. = 0.341E+01
4TH CEN. MOMENT OF DISTR. = 0.264E+03
MINIMUM LATERAL VEL = -7.94
MAXIMUM LATERAL VEL = 7.94

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-7.15	4	0.7129E-02	0.3357E-0
-5.56	23	0.2733E-01	0.2995E-0
-3.97	47	0.5504E-01	0.9655E-0
-2.38	75	0.8911E-01	0.2070E+0
-0.79	118	0.1402E+00	0.3903E+0
0.79	74	0.8792E-01	0.3812E+0
2.38	67	0.1034E+00	0.7209E+0
3.97	47	0.5584E-01	0.8622E+0
5.56	35	0.4139E-01	0.9339E+0
7.15	17	0.2020E-01	0.9905E+0

EXPERIMENT # 47

FLOW PARAMETERS UGS = 17.5 M/S RE(GAS) = 0.62E+05
ULS = 0.121 M/S RE(LIQ) = 0.62E+04

STATISTICAL ANALYSIS OF LATERAL VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 520 DROPLETS

AVERAGE LATERAL VEL = -0.16 +/- 0.29
MEDIAN LATERAL VEL = -0.35
STANDARD DEVIATION = 9.43
3RD CEN. MOMENT OF DISTR. = 0.483E+01
4TH CEN. MOMENT OF DISTR. = 0.317E+03
MINIMUM LATERAL VEL = -7.75
MAXIMUM LATERAL VEL = 7.75

LATERAL V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
-6.98	9	0.1112E-01	-0.1980E-0
-5.43	53	0.4550E-01	0.5374E-0
-3.88	50	0.1800E-01	0.1533E+0
-2.33	70	0.8652E-01	0.2621E+0
-0.78	101	0.1248E+00	0.4331E+0
0.77	69	0.3528E-01	0.5900E+0
2.32	72	0.0699E-01	0.7510E+0
3.87	46	0.5635E-01	0.8473E+0
5.42	33	0.4079E-01	0.9199E+0
6.97	18	0.2225E-01	0.9724E+0

EXPERIMENT # 21

FLOW PARAMETERS UGS = 17.3 M/S RE(GAS) = 0.72E+05
ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 621 DROPLETS

AVERAGE ABS LAT VEL = 2.37 +/- 0.13
MEDIAN ABS LAT VEL = 1.68
STANDARD DEVIATION = 1.48
3RD CEN. MOMENT OF DISTR. = 0.388E+01
4TH CEN. MOMENT OF DISTR. = 0.251E+02
MINIMUM ABS LAT VEL = 0.00
MAXIMUM ABS LAT VEL = 7.66

ABS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
0.38	124	0.2607E+00	0.1193E+0
1.15	100	0.2102E+00	0.2805E+0
1.91	114	0.3397E+00	0.4618E+0
2.68	99	0.2081E+00	0.6360E+0
3.45	72	0.1514E+00	0.7750E+0
4.21	39	0.8199E-01	0.8435E+0
4.98	31	0.6517E-01	0.9177E+0
5.74	21	0.4415E-01	0.9606E+0
6.51	10	0.2102E-01	0.7649E+0
7.28	10	0.2102E-01	0.9987E+0

EXPERIMENT # 23

FLOW PARAMETERS UGS = 13.9 M/S RE(GAS) = 0.58E+05
ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 577 DROPLETS

AVERAGE ABS LAT VEL = 2.29 +/- 0.14
MEDIAN ABS LAT VEL = 1.98
STANDARD DEVIATION = 1.76
3RD CEN. MOMENT OF DISTR. = 0.441E+01
4TH CEN. MOMENT OF DISTR. = 0.260E+02
MINIMUM ABS LAT VEL = 0.00
MAXIMUM ABS LAT VEL = 7.88

ABS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
0.39	154	0.3387E+00	0.1712E+0
1.18	86	0.1891E+00	0.3605E+0
1.97	93	0.2045E+00	0.5126E+0
2.76	85	0.1849E+00	0.6716E+0
3.55	53	0.1164E+00	0.7920E+0
4.33	36	0.7910E-01	0.8651E+0
5.12	37	0.6130E-01	0.9295E+0
5.91	16	0.3519E-01	0.9766E+0
6.70	10	0.2199E-01	0.7964E+0
7.49	6	0.1320E-01	0.1012E+0

EXPERIMENT # 25

FLOW PARAMETERS UGS = 14.1 M/S RE(GAS) = 0.30E+04
ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 563 DROPLETS

AVERAGE ABS LAT VEL = 2.03 +/- 0.13
MEDIAN ABS LAT VEL = 1.84
STANDARD DEVIATION = 1.54
3RD CEN. MOMENT OF DISTR. = 0.331E+01
4TH CEN. MOMENT OF DISTR. = 0.186E+02
MINIMUM ABS LAT VEL = 0.00
MAXIMUM ABS LAT VEL = 7.90

ABS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
0.39	163	0.3665E+00	0.2242E+0
1.18	74	0.1709E+00	0.3905E+0
1.97	100	0.2923E+00	0.5777E+0
2.76	84	0.1590E+00	0.7785E+0
3.55	41	0.9218E-01	0.8652E+0
4.34	21	0.4722E-01	0.9351E+0
5.13	32	0.7195E-01	0.9832E+0
5.92	9	0.2024E-01	0.1022E+0
6.71	5	0.1124E-01	0.1031E+0
7.50	1	0.2240E-02	0.1040E+0

EXPERIMENT # 22

FLOW PARAMETERS UGS = 17.6 M/S RE(GAS) = 0.65E+05
ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 579 DROPLETS

AVERAGE ABS LAT VEL = 2.10 +/- 0.13
MEDIAN ABS LAT VEL = 1.94
STANDARD DEVIATION = 1.58
3RD CEN. MOMENT OF DISTR. = 0.308E+01
4TH CEN. MOMENT OF DISTR. = 0.181E+02
MINIMUM ABS LAT VEL = 0.00
MAXIMUM ABS LAT VEL = 7.94

ABS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
0.40	141	0.3067E+00	0.1532E+0
1.19	97	0.2110E+00	0.3422E+0
1.98	115	0.2501E+00	0.5260E+0
2.78	92	0.2001E+00	0.7114E+0
3.57	50	0.1008E+00	0.8326E+0
4.37	39	0.7170E-01	0.9008E+0
5.16	27	0.5873E-01	0.9524E+0
5.95	13	0.3915E-01	0.9921E+0
6.75	5	0.1000E-01	0.1012E+0
7.54	0	0.0000E+00	0.1014E+0

EXPERIMENT # 24

FLOW PARAMETERS UGS = 14.0 M/S RE(GAS) = 0.52E+05
ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 554 DROPLETS

AVERAGE ABS LAT VEL = 2.11 +/- 0.13
MEDIAN ABS LAT VEL = 1.87
STANDARD DEVIATION = 1.59
3RD CEN. MOMENT OF DISTR. = 0.336E+01
4TH CEN. MOMENT OF DISTR. = 0.193E+02
MINIMUM ABS LAT VEL = 0.00
MAXIMUM ABS LAT VEL = 7.90

ABS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
0.39	153	0.3496E+00	0.2055E+0
1.18	80	0.1820E+00	0.3771E+0
1.97	120	0.2742E+00	0.5623E+0
2.76	74	0.1691E+00	0.7450E+0
3.55	47	0.1074E+00	0.8492E+0
4.34	31	0.7083E-01	0.9184E+0
5.13	27	0.6169E-01	0.9702E+0
5.92	16	0.3634E-01	0.1010E+0
6.71	4	0.9140E-02	0.1038E+0
7.50	1	0.2285E-02	0.1030E+0

EXPERIMENT # 26

FLOW PARAMETERS UGS = 24.7 M/S RE(GAS) = 0.95E+05
ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 676 DROPLETS

AVERAGE ABS LAT VEL = 2.73 +/- 0.14
MEDIAN ABS LAT VEL = 2.46
STANDARD DEVIATION = 1.80
3RD CEN. MOMENT OF DISTR. = 0.330E+01
4TH CEN. MOMENT OF DISTR. = 0.280E+02
MINIMUM ABS LAT VEL = 0.00
MAXIMUM ABS LAT VEL = 7.32

ABS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
0.38	129	0.2530E+00	0.1180E+0
1.18	79	0.1534E+00	0.2603E+0
1.97	98	0.1920E+00	0.3859E+0
2.76	113	0.2262E+00	0.5516E+0
3.55	57	0.1121E+00	0.6500E+0
4.34	36	0.1102E+00	0.7576E+0
5.13	35	0.1082E+00	0.8414E+0
5.92	48	0.9442E-01	0.9190E+0
6.71	24	0.4721E-01	0.9733E+0
7.50	14	0.2754E-01	0.9969E+0

EXPERIMENT # 27

FLOW PARAMETERS UGS = 24.5 M/S RE(GAS) = 0.96E+05
ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF ADS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 365 DROPLETS

AVERAGE ADS LAT VEL = 2.75 +/- 0.13
MEDIAN ADS LAT VEL = 2.41
STANDARD DEVIATION = 1.84
3RD CEN. MOMENT OF DISTR. = 0.249E+01
4TH CEN. MOMENT OF DISTR. = 0.230E+02
MINIMUM ADS LAT VEL = 0.00
MAXIMUM ADS LAT VEL = 7.65

ADS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
0.30	101	0.2257E+00	0.1099E+0
1.15	80	0.1790E+00	0.2503E+0
1.91	100	0.2235E+00	0.4068E+0
2.68	76	0.1690E+00	0.5622E+0
3.44	50	0.1117E+00	0.6649E+0
4.21	31	0.1140E+00	0.7495E+0
4.97	62	0.1385E+00	0.8402E+0
5.74	44	0.9832E-01	0.9429E+0
6.50	18	0.4022E-01	0.9940E+0
7.27	2	0.4469E-02	0.1010E+0

EXPERIMENT # 29

FLOW PARAMETERS UGS = 21.5 M/S RE(GAS) = 0.83E+05
ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF ADS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 365 DROPLETS

AVERAGE ADS LAT VEL = 3.01 +/- 0.16
MEDIAN ADS LAT VEL = 2.77
STANDARD DEVIATION = 1.92
3RD CEN. MOMENT OF DISTR. = 0.224E+01
4TH CEN. MOMENT OF DISTR. = 0.284E+02
MINIMUM ADS LAT VEL = 0.00
MAXIMUM ADS LAT VEL = 7.94

ADS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
0.40	96	0.2047E+00	0.1122E+0
1.19	61	0.1313E+00	0.3295E+0
1.98	92	0.1931E+00	0.3504E+0
2.78	89	0.1916E+00	0.5209E+0
3.57	32	0.1100E+00	0.6401E+0
4.37	57	0.1207E+00	0.7271E+0
5.16	71	0.1520E+00	0.8407E+0
5.95	42	0.9042E-01	0.9412E+0
6.75	16	0.3445E-01	0.9882E+0
7.54	8	0.1722E-01	0.1006E+0

EXPERIMENT # 31

FLOW PARAMETERS UGS = 21.6 M/S RE(GAS) = 0.82E+05
ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ADS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 376 DROPLETS

AVERAGE ADS LAT VEL = 2.77 +/- 0.13
MEDIAN ADS LAT VEL = 2.49
STANDARD DEVIATION = 1.81
3RD CEN. MOMENT OF DISTR. = 0.282E+01
4TH CEN. MOMENT OF DISTR. = 0.251E+02
MINIMUM ADS LAT VEL = 0.00
MAXIMUM ADS LAT VEL = 6.00

ADS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
0.40	93	0.2062E+00	0.1012E+0
1.20	82	0.1780E+00	0.2430E+0
2.00	101	0.2175E+00	0.4044E+0
2.80	82	0.1780E+00	0.5674E+0
3.60	62	0.1345E+00	0.6902E+0
4.40	58	0.1259E+00	0.7926E+0
5.20	33	0.1150E+00	0.8910E+0
6.00	25	0.3425E-01	0.9403E+0
6.80	12	0.2604E-01	0.9897E+0
7.60	3	0.1085E-01	0.1005E+0

EXPERIMENT # 28

FLOW PARAMETERS UGS = 24.7 M/S RE(GAS) = 0.96E+05
ULS = 0.069 M/S RE(LIQ) = 0.33E+04

STATISTICAL ANALYSIS OF ADS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 390 DROPLETS

AVERAGE ADS LAT VEL = 2.98 +/- 0.13
MEDIAN ADS LAT VEL = 2.66
STANDARD DEVIATION = 1.89
3RD CEN. MOMENT OF DISTR. = 0.239E+01
4TH CEN. MOMENT OF DISTR. = 0.272E+02
MINIMUM ADS LAT VEL = 0.00
MAXIMUM ADS LAT VEL = 8.00

ADS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
0.40	103	0.2182E+00	0.1203E+0
1.20	69	0.1462E+00	0.2464E+0
2.00	97	0.2053E+00	0.3893E+0
2.80	76	0.1610E+00	0.5413E+0
3.60	59	0.1250E+00	0.6507E+0
4.40	73	0.1547E+00	0.7624E+0
5.20	60	0.1271E+00	0.8794E+0
6.00	33	0.6992E-01	0.9586E+0
6.80	10	0.2119E-01	0.9933E+0
7.60	8	0.1695E-01	0.1004E+0

EXPERIMENT # 30

FLOW PARAMETERS UGS = 21.6 M/S RE(GAS) = 0.82E+05
ULS = 0.069 M/S RE(LIQ) = 0.33E+04

STATISTICAL ANALYSIS OF ADS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 368 DROPLETS

AVERAGE ADS LAT VEL = 2.71 +/- 0.13
MEDIAN ADS LAT VEL = 2.41
STANDARD DEVIATION = 1.83
3RD CEN. MOMENT OF DISTR. = 0.317E+01
4TH CEN. MOMENT OF DISTR. = 0.271E+02
MINIMUM ADS LAT VEL = 0.00
MAXIMUM ADS LAT VEL = 7.96

ADS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
0.40	116	0.2478E+00	0.1368E+0
1.19	73	0.1560E+00	0.2753E+0
1.99	102	0.2179E+00	0.4259E+0
2.79	82	0.1752E+00	0.5875E+0
3.59	43	0.1346E+00	0.7091E+0
4.38	31	0.1090E+00	0.8044E+0
5.17	50	0.1606E+00	0.8908E+0
5.97	32	0.6837E-01	0.9626E+0
6.77	13	0.2777E-01	0.9990E+0
7.56	5	0.1068E-01	0.1013E+0

EXPERIMENT # 32

FLOW PARAMETERS UGS = 17.1 M/S RE(GAS) = 0.64E+05
ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF ADS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE 380 DROPLETS

AVERAGE ADS LAT VEL = 2.61 +/- 0.14
MEDIAN ADS LAT VEL = 2.35
STANDARD DEVIATION = 1.76
3RD CEN. MOMENT OF DISTR. = 0.284E+01
4TH CEN. MOMENT OF DISTR. = 0.227E+02
MINIMUM ADS LAT VEL = 0.00
MAXIMUM ADS LAT VEL = 7.95

ADS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS.
0.40	109	0.2364E+00	0.1123E+0
1.19	37	0.1887E+00	0.2709E+0
1.99	98	0.2125E+00	0.4313E+0
2.78	84	0.1865E+00	0.5929E+0
3.58	60	0.1475E+00	0.7267E+0
4.37	40	0.0675E-01	0.8170E+0
5.17	50	0.1084E+00	0.8928E+0
5.96	34	0.7374E-01	0.9703E+0
6.76	3	0.4504E-02	0.1001E+0
7.55	4	0.8675E-02	0.9991E+0

EXPERIMENT # 33

FLOW PARAMETERS UGS = 17.4 M/S RE(GAS) = 0.64E+03
 ULS = 0.069 M/S RE(LIQ) = 0.34E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION
 SAMPLE SIZE 573 DROPLETS

AVERAGE ABS LAT VEL = 2.92 +/- 0.13
 MEDIAN ABS LAT VEL = 2.49
 STANDARD DEVIATION = 1.83
 3RD CEN. MOMENT OF DISTR. = 0.249E+01
 4TH CEN. MOMENT OF DISTR. = 0.266E+02
 MINIMUM ABS LAT VEL = 0.00
 MAXIMUM ABS LAT VEL = 7.80

ABS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
0.39	87	0.1927E+00	0.9815E-0
1.18	70	0.1550E+00	0.3211E+0
1.97	95	0.2104E+00	0.3649E+0
2.76	82	0.1816E+00	0.5269E+0
3.55	62	0.1373E+00	0.6499E+0
4.33	62	0.1373E+00	0.7537E+0
5.12	41	0.1251E+00	0.8644E+0
5.91	31	0.4846E-01	0.9486E+0
6.70	12	0.2658E-01	0.9831E+0
7.49	10	0.2215E-01	0.1000E+0

EXPERIMENT # 34

FLOW PARAMETERS UGS = 14.5 M/S RE(GAS) = 0.52E+03
 ULS = 0.069 M/S RE(LIQ) = 0.34E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION
 SAMPLE SIZE 568 DROPLETS

AVERAGE ABS LAT VEL = 2.77 +/- 0.15
 MEDIAN ABS LAT VEL = 2.30
 STANDARD DEVIATION = 1.82
 3RD CEN. MOMENT OF DISTR. = 0.277E+01
 4TH CEN. MOMENT OF DISTR. = 0.251E+02
 MINIMUM ABS LAT VEL = 0.00
 MAXIMUM ABS LAT VEL = 7.85

ABS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
0.39	99	0.2220E+00	0.1258E+0
1.18	63	0.1453E+00	0.2464E+0
1.96	104	0.2032E+00	0.3973E+0
2.75	86	0.1929E+00	0.5720E+0
3.53	59	0.1322E+00	0.6976E+0
4.32	50	0.1121E+00	0.7905E+0
5.10	52	0.1166E+00	0.8816E+0
5.89	33	0.7401E-01	0.9587E+0
6.67	14	0.3140E-01	0.9989E+0
7.46	5	0.1121E-01	0.1014E+0

EXPERIMENT # 40

FLOW PARAMETERS UGS = 24.6 M/S RE(GAS) = 0.94E+03
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION
 SAMPLE SIZE 377 DROPLETS

AVERAGE ABS LAT VEL = 2.17 +/- 0.14
 MEDIAN ABS LAT VEL = 1.89
 STANDARD DEVIATION = 1.66
 3RD CEN. MOMENT OF DISTR. = 0.411E+01
 4TH CEN. MOMENT OF DISTR. = 0.245E+02
 MINIMUM ABS LAT VEL = 0.00
 MAXIMUM ABS LAT VEL = 7.94

ABS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
0.40	155	0.3340E+00	0.1607E+0
1.19	98	0.2139E+00	0.3650E+0
1.98	98	0.2139E+00	0.5322E+0
2.78	90	0.1944E+00	0.6985E+0
3.57	38	0.1266E+00	0.8295E+0
4.37	25	0.5437E-01	0.8979E+0
5.16	10	0.3929E-01	0.9779E+0
5.95	8	0.1746E-01	0.1000E+0
6.75	3	0.6540E-02	0.1009E+0
7.54	3		

EXPERIMENT # 41

FLOW PARAMETERS UGS = 24.4 M/S RE(GAS) = 0.95E+03
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION
 SAMPLE SIZE 538 DROPLETS

AVERAGE ABS LAT VEL = 2.28 +/- 0.14
 MEDIAN ABS LAT VEL = 2.03
 STANDARD DEVIATION = 1.71
 3RD CEN. MOMENT OF DISTR. = 0.380E+01
 4TH CEN. MOMENT OF DISTR. = 0.252E+02
 MINIMUM ABS LAT VEL = 0.00
 MAXIMUM ABS LAT VEL = 7.89

ABS LAT V CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
0.39	143	0.3369E+00	0.1809E+0
1.18	72	0.1696E+00	0.3536E+0
1.97	90	0.2120E+00	0.5037E+0
2.76	83	0.1935E+00	0.6696E+0
3.55	59	0.1390E+00	0.8030E+0
4.34	34	0.8010E-01	0.8972E+0
5.13	29	0.6022E-01	0.9444E+0
5.92	17	0.4005E-01	0.9887E+0
6.71	4	0.9423E-02	0.1007E+0
7.50	6	0.1413E-01	0.1013E+0

EXPERIMENT # 42

FLOW PARAMETERS UGS = 24.6 M/S RE(GAS) = 0.94E+05
ULS = 0.121 M/S RE(LIQ) = 0.65E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 590 DROPLETS

AVERAGE ABS LAT VEL = 2.62 +/- 0.15
MEDIAN ABS LAT VEL = 2.34
STANDARD DEVIATION = 1.65
3RD CEN. MOMENT OF DISTR. = 0.351E+01
4TH CEN. MOMENT OF DISTR. = 0.280E+02
MINIMUM ABS LAT VEL = 0.00
MAXIMUM ABS LAT VEL = 7.97

ABS LAT V CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
0.40	132	0.2807E+00	0.1590E+0
1.20	70	0.1489E+00	0.3038E+0
1.99	99	0.2105E+00	0.4477E+0
2.79	81	0.1723E+00	0.6059E+0
3.59	60	0.1340E+00	0.7262E+0
4.38	50	0.1043E+00	0.8191E+0
5.18	56	0.1191E+00	0.9114E+0
5.98	21	0.4466E-01	0.9792E+0
6.77	6	0.1701E-01	0.9991E+0
7.57	9	0.1914E-01	0.1014E+0

EXPERIMENT # 43

FLOW PARAMETERS UGS = 24.6 M/S RE(GAS) = 0.94E+05
ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 587 DROPLETS

AVERAGE ABS LAT VEL = 2.69 +/- 0.15
MEDIAN ABS LAT VEL = 2.42
STANDARD DEVIATION = 1.64
3RD CEN. MOMENT OF DISTR. = 0.313E+01
4TH CEN. MOMENT OF DISTR. = 0.266E+02
MINIMUM ABS LAT VEL = 0.00
MAXIMUM ABS LAT VEL = 7.64

ABS LAT V CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
0.38	111	0.2475E+00	0.1160E+0
1.15	77	0.1717E+00	0.2646E+0
1.91	90	0.2007E+00	0.4050E+0
2.67	98	0.1962E+00	0.5620E+0
3.44	54	0.1204E+00	0.6835E+0
4.20	50	0.1115E+00	0.7654E+0
4.97	65	0.1449E+00	0.8686E+0
5.73	22	0.4906E-01	0.9447E+0
6.49	20	0.4400E-01	0.9745E+0
7.26	9	0.2007E-01	0.1003E+0

EXPERIMENT # 44

FLOW PARAMETERS UGS = 17.7 M/S RE(GAS) = 0.63E+05
ULS = 0.004 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 577 DROPLETS

AVERAGE ABS LAT VEL = 2.14 +/- 0.13
MEDIAN ABS LAT VEL = 1.80
STANDARD DEVIATION = 1.63
3RD CEN. MOMENT OF DISTR. = 0.391E+01
4TH CEN. MOMENT OF DISTR. = 0.228E+02
MINIMUM ABS LAT VEL = 0.00
MAXIMUM ABS LAT VEL = 7.91

ABS LAT V CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
0.40	155	0.3396E+00	0.1529E+0
1.19	107	0.2344E+00	0.3729E+0
1.98	93	0.2038E+00	0.5434E+0
2.77	82	0.1797E+00	0.6973E+0
3.56	52	0.1139E+00	0.8142E+0
4.35	35	0.7669E-01	0.8869E+0
5.14	20	0.4135E-01	0.9414E+0
5.93	15	0.3237E-01	0.9793E+0
6.72	6	0.1215E-01	0.9965E+0
7.51	3	0.6573E-02	0.1004E+0

EXPERIMENT # 45

FLOW PARAMETERS UGS = 17.5 M/S RE(GAS) = 0.63E+05
ULS = 0.121 M/S RE(LIQ) = 0.64E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 547 DROPLETS

AVERAGE ABS LAT VEL = 2.13 +/- 0.14
MEDIAN ABS LAT VEL = 1.79
STANDARD DEVIATION = 1.62
3RD CEN. MOMENT OF DISTR. = 0.361E+01
4TH CEN. MOMENT OF DISTR. = 0.206E+02
MINIMUM ABS LAT VEL = 0.00
MAXIMUM ABS LAT VEL = 7.23

ABS LAT V CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
0.36	131	0.3312E+00	0.1226E+0
1.08	103	0.2604E+00	0.3385E+0
1.81	83	0.2099E+00	0.5041E+0
2.53	81	0.2048E+00	0.6373E+0
3.25	40	0.1011E+00	0.7655E+0
3.98	39	0.9861E-01	0.8345E+0
4.70	41	0.1037E+00	0.9123E+0
5.42	12	0.3034E-01	0.9613E+0
6.15	8	0.2023E-01	0.9754E+0
6.87	0	0.2023E-01	0.9930E+0

EXPERIMENT # 46

FLOW PARAMETERS UGS = 17.7 M/S RE(GAS) = 0.62E+05
ULS = 0.034 M/S RE(LIQ) = 0.19E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 530 DROPLETS

AVERAGE ABS LAT VEL = 2.58 +/- 0.16
MEDIAN ABS LAT VEL = 2.23
STANDARD DEVIATION = 1.86
3RD CEN. MOMENT OF DISTR. = 0.437E+01
4TH CEN. MOMENT OF DISTR. = 0.312E+02
MINIMUM ABS LAT VEL = 0.00
MAXIMUM ABS LAT VEL = 7.94

ABS LAT V CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
0.40	110	0.2614E+00	0.1253E+0
1.19	82	0.1949E+00	0.2949E+0
1.98	89	0.2115E+00	0.4367E+0
2.78	73	0.1735E+00	0.6134E+0
3.57	50	0.1188E+00	0.7278E+0
4.37	44	0.1046E+00	0.8142E+0
5.16	29	0.7260E-01	0.8948E+0
5.95	19	0.4315E-01	0.9493E+0
6.75	16	0.2802E-01	0.9800E+0
7.54	7	0.1663E-01	0.1006E+0

EXPERIMENT # 47

FLOW PARAMETERS UGS = 17.5 M/S RE(GAS) = 0.62E+05
ULS = 0.121 M/S RE(LIQ) = 0.62E+04

STATISTICAL ANALYSIS OF ABS LAT VEL --- NUMBER DISTRIBUTION

SAMPLE SIZE : 522 DROPLETS

AVERAGE ABS LAT VEL = 2.60 +/- 0.17
MEDIAN ABS LAT VEL = 2.49
STANDARD DEVIATION = 1.93
3RD CEN. MOMENT OF DISTR. = 0.336E+01
4TH CEN. MOMENT OF DISTR. = 0.300E+02
MINIMUM ABS LAT VEL = 0.00
MAXIMUM ABS LAT VEL = 7.75

ABS LAT V CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
0.39	98	0.2422E+00	0.1129E+0
1.16	72	0.1780E+00	0.2653E+0
1.94	77	0.1903E+00	0.4086E+0
2.71	65	0.1473E+00	0.5473E+0
3.49	48	0.1187E+00	0.6547E+0
4.26	40	0.1187E+00	0.7429E+0
5.04	60	0.1403E+00	0.8502E+0
5.81	26	0.6427E-01	0.9355E+0
6.59	15	0.2708E-01	0.9497E+0
7.36	12	0.2966E-01	0.9930E+0

EXPERIMENT # 21

FLOW PARAMETERS : UGS = 19.5 M/S RE(GAS) = 0.72E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION

SAMPLE SIZE : 621 DROPLETS

AVERAGE ANGLE = 8.03 +/- 0.40
 MEDIAN ANGLE = 6.89
 STANDARD DEVIATION = 6.13
 3RD CEN. MOMENT OF DISTR. = 0.237E+03
 4TH CEN. MOMENT OF DISTR. = 0.707E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 41.51

ANGLE	CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.04		71	0.7764E-01	0.7450E-0
3.11		63	0.7100E-01	0.2337E+0
5.19		65	0.6638E-01	0.3709E+0
7.26		76	0.3220E-01	0.5306E+0
9.34		71	0.4420E-01	0.6628E+0
11.42		51	0.4803E-01	0.7550E+0
13.49		40	0.2372E-01	0.8331E+0
15.57		44	0.2011E-01	0.8730E+0
17.64		29	0.1680E-01	0.9150E+0
19.72		20	0.9179E-02	0.9414E+0
21.79		18	0.9398E-02	0.9601E+0
23.87		14	0.6119E-02	0.9770E+0
25.94		10	0.2186E-02	0.9852E+0
28.02		7	0.1257E-02	0.9884E+0
30.10		6	0.8742E-03	0.9906E+0
32.17		3	0.1639E-03	0.9917E+0
34.25		3	0.2732E-03	0.9917E+0
36.32		3	0.1475E-02	0.9939E+0
38.40		3	0.2732E-03	0.9940E+0
40.47		1	0.5464E-04	0.9957E+0

EXPERIMENT # 22

FLOW PARAMETERS : UGS = 17.8 M/S RE(GAS) = 0.65E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION

SAMPLE SIZE : 579 DROPLETS

AVERAGE ANGLE = 7.81 +/- 0.49
 MEDIAN ANGLE = 7.04
 STANDARD DEVIATION = 6.03
 3RD CEN. MOMENT OF DISTR. = 0.246E+03
 4TH CEN. MOMENT OF DISTR. = 0.591E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 36.77

ANGLE	CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
0.92		72	0.6866E-01	0.7568E-0
2.76		73	0.8250E-01	0.2386E+0
4.60		67	0.5789E-01	0.3677E+0
6.43		45	0.5182E-01	0.4639E+0
8.27		51	0.7626E-01	0.5810E+0
10.11		35	0.6003E-01	0.7149E+0
11.95		43	0.2007E-01	0.7831E+0
13.79		43	0.3309E-01	0.8339E+0
15.63		29	0.2292E-01	0.8946E+0
17.46		24	0.1284E-01	0.9245E+0
19.30		23	0.1250E-01	0.9482E+0
21.14		12	0.5530E-02	0.9650E+0
22.98		10	0.4016E-02	0.9738E+0
24.82		11	0.2408E-02	0.9810E+0
26.66		3	0.2676E-03	0.9824E+0
28.49		6	0.4016E-02	0.9876E+0
30.33		3	0.2676E-03	0.9926E+0
32.17		5	0.1873E-02	0.9940E+0
34.01		1	0.8919E-04	0.9944E+0
35.85		3	0.2676E-03	0.9955E+0

EXPERIMENT # 23

FLOW PARAMETERS : UGS = 15.9 M/S RE(GAS) = 0.50E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION

SAMPLE SIZE : 577 DROPLETS

AVERAGE ANGLE = 7.37 +/- 0.54
 MEDIAN ANGLE = 5.62
 STANDARD DEVIATION = 6.27
 3RD CEN. MOMENT OF DISTR. = 0.370E+03
 4TH CEN. MOMENT OF DISTR. = 0.933E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 48.70

ANGLE	CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.22		114	0.1330E+00	0.2172E+0
3.66		73	0.5548E-01	0.4214E+0
6.10		50	0.5428E-01	0.5499E+0
8.54		77	0.4809E-01	0.6705E+0
10.98		52	0.3166E-01	0.7755E+0
13.42		36	0.2475E-01	0.8420E+0
15.85		45	0.2203E-01	0.9007E+0
18.29		28	0.1508E-01	0.9469E+0
20.73		30	0.1145E-01	0.9798E+0
23.17		15	0.3274E-02	0.9973E+0
25.61		8	0.5231E-02	0.1007E+0
28.05		9	0.1872E-02	0.1016E+0
30.49		9	0.8839E-03	0.1019E+0
32.93		9	0.9879E-03	0.1021E+0
35.37		4	0.2080E-03	0.1023E+0
37.81		1	0.2600E-03	0.1023E+0
40.25		1	0.2080E-03	0.1024E+0
42.69		0	0.5199E-04	0.1024E+0
45.13		0	0.0000E+00	0.1024E+0
47.56		3	0.1560E-03	0.1024E+0

EXPERIMENT # 24

FLOW PARAMETERS : UGS = 14.0 M/S RE(GAS) = 0.52E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION

SAMPLE SIZE : 554 DROPLETS

AVERAGE ANGLE = 8.43 +/- 0.53
 MEDIAN ANGLE = 6.99
 STANDARD DEVIATION = 6.63
 3RD CEN. MOMENT OF DISTR. = 0.417E+03
 4TH CEN. MOMENT OF DISTR. = 0.128E+05
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 75.73

ANGLE	CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.89	136	0.7893E-01	0.1575E+0	
3.68	98	0.6283E-01	0.4254E+0	
5.47	94	0.4840E-01	0.6355E+0	
7.25	79	0.3584E-01	0.7944E+0	
9.04	50	0.2230E-01	0.9066E+0	
10.83	30	0.4656E-02	0.9546E+0	
12.61	26	0.5634E-02	0.9704E+0	
14.40	17	0.4283E-02	0.9914E+0	
16.19	6	0.2297E-03	0.9993E+0	
17.97	5	0.1437E-03	0.9991E+0	
19.74	3	0.4886E-03	0.1001E+0	
21.55	1	0.1437E-03	0.1002E+0	
23.33	2	0.5748E-04	0.1002E+0	
25.12	1	0.8623E-04	0.1002E+0	
26.91	1	0.2874E-04	0.1003E+0	
28.69	0	0.0000E+00	0.1003E+0	
30.48	0	0.0000E+00	0.1003E+0	
32.27	0	0.0000E+00	0.1003E+0	
34.05	0	0.0000E+00	0.1003E+0	
35.84	1	0.2874E-04	0.1003E+0	

EXPERIMENT # 25

FLOW PARAMETERS : UG5 = 14.1 M/S RE(GAS) = 0.50E+04
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 563 DROPLETS

AVERAGE ANGLE = 7.70 +/- 0.52
 MEDIAN ANGLE = 6.29
 STANDARD DEVIATION = 6.34
 3RD CEN. MOMENT OF DISTR. = 0.405E+03
 4TH CEN. MOMENT OF DISTR. = 0.107E+05
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 55.54

ANGLE	CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
1.39		127	0.8494E-01	0.9345E-0
4.17		73	0.8170E-01	0.3432E+0
6.94		76	0.5520E-01	0.5259E+0
9.72		87	0.6418E-01	0.6947E+0
12.50		55	0.2510E-01	0.8224E+0
15.27		46	0.1665E-01	0.8741E+0
18.05		29	0.9068E-02	0.9098E+0
20.83		21	0.1012E-01	0.9361E+0
23.61		16	0.4118E-02	0.9563E+0
26.38		9	0.4249E-02	0.9764E+0
29.16		12	0.2270E-02	0.9822E+0
31.94		4	0.1927E-02	0.9852E+0
34.71		1	0.4381E-04	0.9852E+0
37.49		1	0.4381E-04	0.9847E+0
40.27		1	0.4381E-04	0.9847E+0
43.05		2	0.8761E-04	0.9851E+0
45.82		0	0.0000E+00	0.9852E+0
48.60		1	0.3066E-03	0.9856E+0
51.38		0	0.0000E+00	0.9862E+0
54.15		1	0.4391E-04	0.9860E+0

EXPERIMENT # 26

FLOW PARAMETERS : UG5 = 24.7 M/S RE(GAS) = 0.95E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 676 DROPLETS

AVERAGE ANGLE = 9.21 +/- 0.50
 MEDIAN ANGLE = 7.93
 STANDARD DEVIATION = 6.63
 3RD CEN. MOMENT OF DISTR. = 0.254E+03
 4TH CEN. MOMENT OF DISTR. = 0.736E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 55.66

ANGLE	CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
1.40		122	0.7177E-01	0.1332E+0
4.19		79	0.5249E-01	0.2875E+0
6.90		106	0.6498E-01	0.4567E+0
9.70		80	0.4425E-01	0.6104E+0
12.57		70	0.4303E-01	0.7322E+0
15.36		47	0.2378E-01	0.8236E+0
18.15		61	0.3553E-01	0.9033E+0
20.95		31	0.1298E-01	0.9724E+0
23.74		17	0.4945E-02	0.9936E+0
26.53		12	0.1568E-02	0.1002E+0
29.33		14	0.3136E-02	0.1009E+0
32.12		4	0.3484E-03	0.1014E+0
34.91		4	0.5226E-03	0.1014E+0
37.70		4	0.3484E-03	0.1016E+0
40.50		0	0.0000E+00	0.1016E+0
43.29		1	0.8710E-04	0.1016E+0
46.08		0	0.0000E+00	0.1017E+0
48.88		0	0.0000E+00	0.1017E+0
51.67		1	0.8710E-04	0.1017E+0
54.46		0	0.0000E+00	0.1017E+0

EXPERIMENT # 27

FLOW PARAMETERS : UG5 = 24.5 M/S RE(GAS) = 0.96E+05
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 585 DROPLETS

AVERAGE ANGLE = 8.37 +/- 0.51
 MEDIAN ANGLE = 6.82
 STANDARD DEVIATION = 6.26
 3RD CEN. MOMENT OF DISTR. = 0.329E+03
 4TH CEN. MOMENT OF DISTR. = 0.607E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 61.12

ANGLE	CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
1.33		111	0.7646E-01	0.1127E+0
4.58		90	0.7446E-01	0.3430E+0
7.64		94	0.5514E-01	0.5501E+0
10.70		73	0.3167E-01	0.6701E+0
13.75		61	0.3566E-01	0.7779E+0
16.81		56	0.2914E-01	0.8809E+0
19.86		34	0.1576E-01	0.9498E+0
22.92		30	0.4748E-02	0.9894E+0
25.97		15	0.2752E-02	0.9894E+0
29.03		9	0.8093E-03	0.9950E+0
32.09		6	0.2207E-03	0.9950E+0
35.14		2	0.1079E-03	0.9970E+0
38.20		1	0.5396E-04	0.9972E+0
41.25		1	0.5396E-04	0.9974E+0
44.31		1	0.5396E-04	0.9975E+0
47.37		0	0.0000E+00	0.9976E+0
50.42		0	0.0000E+00	0.9976E+0
53.48		0	0.0000E+00	0.9976E+0
56.53		0	0.0000E+00	0.9976E+0
59.59		1	0.5396E-04	0.9977E+0

EXPERIMENT # 28

FLOW PARAMETERS : UG5 = 24.7 M/S RE(GAS) = 0.96E+05
 ULS = 0.069 M/S RE(LIQ) = 0.33E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 590 DROPLETS

AVERAGE ANGLE = 8.28 +/- 0.49
 MEDIAN ANGLE = 6.93
 STANDARD DEVIATION = 6.13
 3RD CEN. MOMENT OF DISTR. = 0.247E+03
 4TH CEN. MOMENT OF DISTR. = 0.659E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 45.98

ANGLE	CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
1.15		80	0.7429E-01	0.9281E-0
3.45		62	0.6945E-01	0.2536E+0
5.75		62	0.7297E-01	0.4185E+0
8.05		64	0.6005E-01	0.5755E+0
10.34		43	0.3707E-01	0.6846E+0
12.64		53	0.3825E-01	0.7693E+0
14.94		46	0.3010E-01	0.8494E+0
17.24		48	0.2423E-01	0.9116E+0
19.54		31	0.1417E-01	0.9560E+0
21.84		31	0.8002E-02	0.9809E+0
24.14		13	0.2129E-02	0.9921E+0
26.44		11	0.1395E-02	0.9955E+0
28.73		2	0.4405E-03	0.9976E+0
31.03		10	0.8809E-03	0.9991E+0
33.33		5	0.4405E-03	0.1001E+0
35.63		5	0.5139E-03	0.1002E+0
37.93		0	0.0000E+00	0.1002E+0
40.23		3	0.3671E-03	0.1003E+0
42.53		2	0.1468E-03	0.1003E+0
44.83		2	0.1468E-03	0.1004E+0

EXPERIMENT # 27

FLOW PARAMETERS : UGS = 21.5 M/S RE(GAS) = 0.03E+03
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION

SAMPLE SIZE : 585 DROPLETS

AVERAGE ANGLE = 8.91 +/- 0.53
 MEDIAN ANGLE = 7.51
 STANDARD DEVIATION = 6.51
 3RD CEN. MOMENT OF DISTR. = 0.250E+03
 4TH CEN. MOMENT OF DISTR. = 0.613E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 57.17

ANGLE	CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
1.43		82	0.7093E-01	0.1473E+0
4.29		75	0.5294E-01	0.2951E+0
7.15		92	0.8121E-01	0.4941E+0
10.01		83	0.4792E-01	0.6900E+0
12.86		43	0.1844E-01	0.7739E+0
15.72		56	0.3264E-01	0.8472E+0
18.58		42	0.1605E-01	0.9189E+0
21.44		47	0.2032E-01	0.9694E+0
24.30		28	0.5642E-02	0.1009E+0
27.16		17	0.1914E-02	0.1017E+0
30.02		8	0.4702E-03	0.1020E+0
32.88		5	0.7053E-03	0.1022E+0
35.73		2	0.2607E-03	0.1023E+0
38.59		2	0.6717E-04	0.1024E+0
41.45		1	0.3353E-04	0.1024E+0
44.31		0	0.0000E+00	0.1024E+0
47.17		0	0.0000E+00	0.1024E+0
50.03		1	0.3358E-04	0.1024E+0
52.89		0	0.0000E+00	0.1024E+0
55.75		0	0.0000E+00	0.1024E+0

EXPERIMENT # 30

FLOW PARAMETERS : UGS = 21.6 M/S RE(GAS) = 0.82E+05
 ULS = 0.069 M/S RE(LIQ) = 0.30E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION

SAMPLE SIZE : 588 DROPLETS

AVERAGE ANGLE = 8.41 +/- 0.53
 MEDIAN ANGLE = 7.31
 STANDARD DEVIATION = 6.57
 3RD CEN. MOMENT OF DISTR. = 0.269E+03
 4TH CEN. MOMENT OF DISTR. = 0.744E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 53.06

ANGLE	CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
1.33		96	0.9954E-01	0.1783E+0
4.29		64	0.4662E-01	0.3489E+0
7.15		88	0.5590E-01	0.4806E+0
10.01		76	0.5228E-01	0.6316E+0
12.86		54	0.3126E-01	0.7369E+0
15.72		63	0.4625E-01	0.8418E+0
18.58		42	0.1547E-01	0.9273E+0
21.44		34	0.1355E-01	0.9606E+0
24.30		21	0.6668E-02	0.9889E+0
27.16		15	0.4961E-02	0.1003E+0
30.02		14	0.2240E-02	0.1013E+0
32.88		11	0.1547E-02	0.1018E+0
35.73		4	0.3201E-03	0.1020E+0
38.59		0	0.0000E+00	0.1020E+0
41.45		1	0.5334E-04	0.1021E+0
44.31		1	0.5334E-04	0.1021E+0
47.17		0	0.0000E+00	0.1021E+0
50.03		2	0.1067E-03	0.1021E+0
52.89		1	0.5334E-04	0.1021E+0
55.75		1	0.5334E-04	0.1021E+0

EXPERIMENT # 31

FLOW PARAMETERS : UGS = 21.6 M/S RE(GAS) = 0.82E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION

SAMPLE SIZE : 576 DROPLETS

AVERAGE ANGLE = 9.11 +/- 0.54
 MEDIAN ANGLE = 7.30
 STANDARD DEVIATION = 6.63
 3RD CEN. MOMENT OF DISTR. = 0.239E+03
 4TH CEN. MOMENT OF DISTR. = 0.643E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 50.19

ANGLE	CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
1.25		77	0.6943E-01	0.1021E+0
3.76		70	0.6799E-01	0.2651E+0
6.27		67	0.6804E-01	0.4446E+0
8.78		67	0.2842E-01	0.5639E+0
11.29		67	0.3857E-01	0.6397E+0
13.80		57	0.4863E-01	0.7320E+0
16.31		44	0.3892E-01	0.8607E+0
18.82		30	0.9058E-02	0.9261E+0
21.33		21	0.1379E-01	0.9507E+0
23.84		30	0.9456E-02	0.9829E+0
26.35		17	0.3036E-02	0.9976E+0
28.86		9	0.1145E-02	0.1002E+0
31.37		11	0.1244E-02	0.1005E+0
33.88		3	0.4479E-03	0.1007E+0
36.39		1	0.4577E-04	0.1008E+0
38.90		0	0.0000E+00	0.1008E+0
41.41		3	0.1493E-03	0.1008E+0
43.92		0	0.0000E+00	0.1008E+0
46.43		0	0.0000E+00	0.1008E+0
48.94		2	0.9934E-04	0.1008E+0

EXPERIMENT # 32

FLOW PARAMETERS : UGS = 17.1 M/S RE(GAS) = 0.64E+05
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION

SAMPLE SIZE : 580 DROPLETS

AVERAGE ANGLE = 8.20 +/- 0.50
 MEDIAN ANGLE = 7.06
 STANDARD DEVIATION = 6.18
 3RD CEN. MOMENT OF DISTR. = 0.275E+03
 4TH CEN. MOMENT OF DISTR. = 0.808E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 69.97

ANGLE	CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
1.75		124	0.8178E-01	0.1649E+0
5.25		106	0.5991E-01	0.4038E+0
8.75		97	0.5402E-01	0.6030E+0
12.24		78	0.4084E-01	0.7710E+0
15.74		66	0.2653E-01	0.8880E+0
19.24		44	0.1461E-01	0.9600E+0
22.74		27	0.3191E-02	0.9893E+0
26.24		17	0.2192E-02	0.9966E+0
29.74		8	0.1615E-02	0.1004E+0
33.23		3	0.4999E-03	0.1007E+0
36.73		1	0.2692E-03	0.1009E+0
40.23		1	0.3845E-04	0.1009E+0
43.73		2	0.7690E-04	0.1009E+0
47.23		1	0.3845E-04	0.1010E+0
50.73		0	0.0000E+00	0.1010E+0
54.23		0	0.0000E+00	0.1010E+0
57.72		0	0.0000E+00	0.1010E+0
61.22		0	0.0000E+00	0.1010E+0
64.72		0	0.0000E+00	0.1010E+0
68.22		1	0.3845E-04	0.1010E+0

EXPERIMENT # 33

FLOW PARAMETERS : UGS = 17.4 M/S RE(GAS) = 0.64E+05
 ULS = 0.069 M/S RE(LIQ) = 0.34E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 573 DROPLETS

AVERAGE ANGLE = 9.17 +/- 0.38
 MEDIAN ANGLE = 7.82
 STANDARD DEVIATION = 7.06
 3RD CEN. MOMENT OF DISTR. = 0.245E+03
 4TH CEN. MOMENT OF DISTR. = 0.722E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 54.48

ANGLE	CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.36		79	0.9157E-01	0.1414E+0
4.09		70	0.5748E-01	0.3401E+0
6.81		71	0.3942E-01	0.4699E+0
9.53		79	0.3380E-01	0.5650E+0
12.26		60	0.4538E-01	0.6734E+0
14.98		58	0.3451E-01	0.7881E+0
17.71		38	0.2012E-01	0.8564E+0
20.43		41	0.3217E-01	0.9306E+0
23.16		25	0.4719E-02	0.9838E+0
25.88		20	0.3527E-02	0.9892E+0
28.60		15	0.3194E-02	0.1000E+0
31.33		8	0.3813E-03	0.1005E+0
34.05		2	0.1907E-03	0.1005E+0
36.78		3	0.1430E-03	0.1006E+0
39.50		2	0.1907E-03	0.1006E+0
42.23		0	0.0000E+00	0.1006E+0
44.95		0	0.0000E+00	0.1006E+0
47.67		1	0.4767E-04	0.1006E+0
50.40		0	0.0000E+00	0.1006E+0
53.12		1	0.4767E-04	0.1006E+0

EXPERIMENT # 34

FLOW PARAMETERS : UGS = 14.5 M/S RE(GAS) = 0.52E+05
 ULS = 0.069 M/S RE(LIQ) = 0.34E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 568 DROPLETS

AVERAGE ANGLE = 9.63 +/- 0.53
 MEDIAN ANGLE = 8.43
 STANDARD DEVIATION = 6.40
 3RD CEN. MOMENT OF DISTR. = 0.307E+03
 4TH CEN. MOMENT OF DISTR. = 0.639E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 51.97

ANGLE	CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.30		49	0.5694E-01	0.1099E+0
3.90		78	0.4648E-01	0.2203E+0
6.50		61	0.7618E-01	0.3862E+0
9.09		79	0.5123E-01	0.5590E+0
11.69		60	0.3651E-01	0.6665E+0
14.29		60	0.4306E-01	0.7680E+0
16.89		54	0.4153E-01	0.8836E+0
19.49		32	0.1499E-01	0.9576E+0
22.09		18	0.6922E-02	0.9821E+0
24.69		24	0.4640E-02	0.9969E+0
27.28		11	0.3994E-02	0.1008E+0
29.88		8	0.1141E-02	0.1015E+0
32.48		2	0.3043E-03	0.1016E+0
35.08		3	0.4945E-03	0.1017E+0
37.68		3	0.1141E-03	0.1018E+0
40.28		3	0.1141E-03	0.1019E+0
42.80		0	0.0000E+00	0.1019E+0
45.47		1	0.1141E-03	0.1019E+0
48.07		0	0.0000E+00	0.1019E+0
50.67		2	0.7607E-04	0.1019E+0

EXPERIMENT # 40

FLOW PARAMETERS : UGS = 24.6 M/S RE(GAS) = 0.94E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION

SAMPLE SIZE : 577 DROPLETS

AVERAGE ANGLE = 7.93 +/- 0.50
 MEDIAN ANGLE = 7.10
 STANDARD DEVIATION = 6.09
 3RD CEN. MOMENT OF DISTR. = 0.275E+03
 4TH CEN. MOMENT OF DISTR. = 0.745E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 51.53

ANGLE	CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.29		110	0.9014E-01	0.1363E+0
3.87		82	0.5835E-01	0.3186E+0
6.44		70	0.6042E-01	0.4611E+0
9.02		61	0.6888E-01	0.6380E+0
11.60		63	0.4177E-01	0.7837E+0
14.17		51	0.2608E-01	0.8489E+0
16.75		42	0.1225E-01	0.9153E+0
19.33		22	0.1748E-01	0.9540E+0
21.90		22	0.3853E-02	0.9829E+0
24.48		19	0.3922E-02	0.9903E+0
27.06		12	0.2477E-02	0.9995E+0
29.63		8	0.1101E-02	0.1004E+0
32.21		3	0.7549E-03	0.1006E+0
34.79		3	0.2064E-03	0.1007E+0
37.36		0	0.0000E+00	0.1008E+0
39.94		1	0.6881E-04	0.1008E+0
42.52		0	0.0000E+00	0.1008E+0
45.09		2	0.1376E-03	0.1008E+0
47.67		2	0.1376E-03	0.1008E+0
50.25		1	0.6881E-04	0.1008E+0

EXPERIMENT # 41

FLOW PARAMETERS : UGS = 24.4 M/S RE(GAS) = 0.95E+05
 UL5 = 0.121 M/S RE(LIQ) = 0.60E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION

SAMPLE SIZE : 538 DROPLETS

AVERAGE ANGLE = 8.14 +/- 0.55
 MEDIAN ANGLE = 7.06
 STANDARD DEVIATION = 6.46
 3RD CEN. MOMENT OF DISTR. = 0.379E+03
 4TH CEN. MOMENT OF DISTR. = 0.107E+05
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 55.20

ANGLE	CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.38		117	0.9212E-01	0.2170E+0
4.14		60	0.3922E-01	0.3439E+0
6.90		66	0.8926E-01	0.5282E+0
9.66		79	0.5269E-01	0.7391E+0
12.42		54	0.2290E-01	0.8313E+0
15.18		50	0.3265E-01	0.9094E+0
17.94		33	0.9011E-02	0.9688E+0
20.70		22	0.1187E-01	0.9933E+0
23.46		15	0.6679E-02	0.1022E+0
26.22		12	0.1696E-02	0.1032E+0
28.98		5	0.5301E-03	0.1034E+0
31.74		7	0.1166E-02	0.1037E+0
34.50		10	0.1272E-02	0.1040E+0
37.26		1	0.5301E-03	0.1043E+0
40.02		3	0.5301E-03	0.1044E+0
42.78		0	0.0000E+00	0.1045E+0
45.54		1	0.1060E-03	0.1045E+0
48.30		0	0.0000E+00	0.1045E+0
51.06		0	0.0000E+00	0.1045E+0
53.82		1	0.1060E-03	0.1045E+0

EXPERIMENT # 42

FLOW PARAMETERS : UGS = 24.6 M/S RE(GAS) = 0.94E+05
 UL5 = 0.121 M/S RE(LIQ) = 0.65E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION

SAMPLE SIZE : 590 DROPLETS

AVERAGE ANGLE = 9.58 +/- 0.53
 MEDIAN ANGLE = 8.93
 STANDARD DEVIATION = 6.60
 3RD CEN. MOMENT OF DISTR. = 0.261E+03
 4TH CEN. MOMENT OF DISTR. = 0.840E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 49.93

ANGLE	CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.25		102	0.6224E-01	0.7831E-0
3.75		78	0.5604E-01	0.2267E+0
6.24		52	0.5119E-01	0.3593E+0
8.74		76	0.5349E-01	0.4891E+0
11.24		58	0.5337E-01	0.6254E+0
13.73		39	0.4951E-01	0.7607E+0
16.23		39	0.2311E-01	0.8512E+0
18.73		44	0.1846E-01	0.8985E+0
21.22		21	0.1852E-01	0.9467E+0
23.72		26	0.7006E-02	0.9795E+0
26.22		10	0.9431E-03	0.9875E+0
28.71		6	0.1347E-02	0.9997E+0
31.21		7	0.1549E-02	0.9938E+0
33.71		3	0.2021E-03	0.9959E+0
36.20		2	0.1347E-03	0.9961E+0
38.70		3	0.3368E-03	0.9967E+0
41.20		1	0.8757E-03	0.9983E+0
43.69		2	0.1347E-03	0.9997E+0
46.19		0	0.0000E+00	0.9997E+0
48.69		1	0.6736E-04	0.9999E+0

EXPERIMENT # 43

FLOW PARAMETERS : UGS = 24.8 M/S RE(GAS) = 0.94E+05
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION

SAMPLE SIZE : 587 DROPLETS

AVERAGE ANGLE = 8.61 +/- 0.52
 MEDIAN ANGLE = 7.29
 STANDARD DEVIATION = 6.43
 3RD CEN. MOMENT OF DISTR. = 0.241E+03
 4TH CEN. MOMENT OF DISTR. = 0.625E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 40.00

ANGLE	CLASS	NO OF DROPLETS	PROD. DENS.	PROD. DIS
1.00		85	0.7761E-01	0.7938E-0
3.00		57	0.7140E-01	0.2282E+0
5.00		64	0.6594E-01	0.3655E+0
7.00		55	0.5427E-01	0.4889E+0
9.00		55	0.3479E-01	0.5723E+0
11.00		56	0.6145E-01	0.6866E+0
13.00		52	0.4004E-01	0.7766E+0
15.00		37	0.2344E-01	0.8357E+0
17.00		30	0.2419E-01	0.8831E+0
19.00		26	0.1691E-01	0.9248E+0
21.00		23	0.1402E-01	0.9554E+0
23.00		16	0.6851E-02	0.9770E+0
25.00		5	0.1606E-02	0.9841E+0
27.00		9	0.4175E-02	0.9893E+0
29.00		7	0.1392E-02	0.9959E+0
31.00		3	0.5353E-03	0.9974E+0
33.00		2	0.2141E-03	0.9981E+0
35.00		3	0.5353E-03	0.9988E+0
37.00		1	0.3212E-03	0.9998E+0
39.00		1	0.3212E-03	0.1000E+0

EXPERIMENT # 44

FLOW PARAMETERS : UGS = 17.7 M/S RE(GAS) = 0.63E+03
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 577 DROPLETS

AVERAGE ANGLE = 8.66 +/- 0.56
 MEDIAN ANGLE = 6.82
 STANDARD DEVIATION = 6.92
 3RD CEN. MOMENT OF DISTR. = 0.358E+03
 4TH CEN. MOMENT OF DISTR. = 0.931E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 59.37

ANGLE	CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
1.48		131	0.6178E-01	0.1191E+0
4.45		80	0.7127E-01	0.3510E+0
7.42		84	0.5107E-01	0.5334E+0
10.39		73	0.3830E-01	0.6663E+0
13.36		51	0.2641E-01	0.7611E+0
16.33		59	0.2446E-01	0.9340E+0
19.30		29	0.2405E-01	0.9092E+0
22.26		25	0.8153E-02	0.9570E+0
25.23		17	0.6307E-02	0.9743E+0
28.20		3	0.1436E-02	0.9882E+0
31.17		9	0.1589E-02	0.9918E+0
34.14		8	0.5127E-03	0.9953E+0
37.11		2	0.1025E-03	0.9959E+0
40.08		2	0.4102E-03	0.9976E+0
43.04		0	0.0000E+00	0.9974E+0
46.01		0	0.1538E-03	0.9975E+0
48.98		1	0.5127E-04	0.9979E+0
51.95		0	0.0000E+00	0.9979E+0
54.92		0	0.0000E+00	0.9979E+0
57.89		0	0.0000E+00	0.9979E+0

EXPERIMENT # 45

FLOW PARAMETERS : UGS = 17.5 M/S RE(GAS) = 0.63E+03
 ULS = 0.121 M/S RE(LIQ) = 0.64E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 547 DROPLETS

AVERAGE ANGLE = 8.49 +/- 0.59
 MEDIAN ANGLE = 7.43
 STANDARD DEVIATION = 6.30
 3RD CEN. MOMENT OF DISTR. = 0.296E+03
 4TH CEN. MOMENT OF DISTR. = 0.774E+04
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 58.82

ANGLE	CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
1.47		110	0.7296E-01	0.1302E+0
4.41		101	0.6036E-01	0.3126E+0
7.35		93	0.4983E-01	0.5069E+0
10.29		65	0.3421E-01	0.6938E+0
13.23		54	0.3411E-01	0.8246E+0
16.18		33	0.1384E-01	0.8903E+0
19.12		33	0.1703E-01	0.9384E+0
22.06		20	0.5244E-02	0.9752E+0
25.00		16	0.7104E-02	0.9915E+0
27.94		9	0.6202E-03	0.1004E+0
30.88		9	0.1551E-02	0.1004E+0
33.82		4	0.5438E-03	0.1009E+0
36.76		2	0.1692E-03	0.1010E+0
39.70		1	0.3665E-03	0.1011E+0
42.64		0	0.0000E+00	0.1012E+0
45.59		0	0.0000E+00	0.1011E+0
48.53		0	0.0000E+00	0.1012E+0
51.47		1	0.2819E-04	0.1012E+0
54.41		0	0.0000E+00	0.1012E+0
57.35		1	0.2819E-04	0.1012E+0

EXPERIMENT # 47

FLOW PARAMETERS : UGS = 17.5 M/S RE(GAS) = 0.62E+03
 ULS = 0.121 M/S RE(LIQ) = 0.62E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 522 DROPLETS

AVERAGE ANGLE = 10.40 +/- 0.69
 MEDIAN ANGLE = 8.29
 STANDARD DEVIATION = 8.00
 3RD CEN. MOMENT OF DISTR. = 0.620E+03
 4TH CEN. MOMENT OF DISTR. = 0.200E+05
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 75.02

ANGLE	CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
1.08		100	0.5739E-01	0.7910E-0
3.63		96	0.6671E-01	0.3309E+0
9.38		61	0.4384E-01	0.5393E+0
13.13		64	0.3231E-01	0.6784E+0
16.80		47	0.2372E-01	0.7031E+0
20.63		52	0.1825E-01	0.8604E+0
24.30		45	0.1473E-01	0.9235E+0
28.13		18	0.3150E-02	0.9611E+0
31.88		13	0.1059E-02	0.9708E+0
35.63		7	0.6580E-03	0.9731E+0
39.38		6	0.2117E-02	0.9787E+0
43.14		7	0.6008E-03	0.9843E+0
46.89		1	0.2861E-04	0.9850E+0
50.64		0	0.0000E+00	0.9850E+0
54.39		0	0.0000E+00	0.9850E+0
58.14		0	0.0000E+00	0.9850E+0
61.89		3	0.8583E-04	0.9852E+0
65.64		0	0.0000E+00	0.9853E+0
69.39		1	0.2861E-04	0.9854E+0
73.14		0	0.0000E+00	0.9855E+0

EXPERIMENT # 46

FLOW PARAMETERS : UGS = 17.7 M/S RE(GAS) = 0.62E+03
 ULS = 0.034 M/S RE(LIQ) = 0.19E+04

STATISTICAL ANALYSIS OF ANGLE --- VOLUME DISTRIBUTION
 SAMPLE SIZE : 530 DROPLETS

AVERAGE ANGLE = 11.24 +/- 0.79
 MEDIAN ANGLE = 8.71
 STANDARD DEVIATION = 9.24
 3RD CEN. MOMENT OF DISTR. = 0.916E+03
 4TH CEN. MOMENT OF DISTR. = 0.289E+05
 MINIMUM ANGLE = 0.00
 MAXIMUM ANGLE = 65.93

ANGLE	CLASS	NO OF DROPLETS	PROB. DENS.	PROB. DIS
1.65		93	0.6139E-01	0.9663E-0
4.94		76	0.5940E-01	0.3001E+0
8.24		64	0.4804E-01	0.4779E+0
11.54		64	0.3735E-01	0.6183E+0
14.83		50	0.2576E-01	0.7231E+0
18.13		42	0.1597E-01	0.7885E+0
21.43		39	0.1836E-01	0.8463E+0
24.72		22	0.7314E-02	0.8883E+0
28.02		27	0.1384E-01	0.9217E+0
31.32		15	0.7939E-02	0.9612E+0
34.61		6	0.2236E-02	0.9754E+0
37.91		4	0.4159E-02	0.9862E+0
41.21		3	0.6709E-04	0.9935E+0
44.50		0	0.9392E-03	0.9943E+0
47.80		2	0.4473E-04	0.9964E+0
51.10		4	0.1789E-03	0.9964E+0
54.39		4	0.1342E-03	0.9971E+0
57.69		0	0.0000E+00	0.9973E+0
60.99		1	0.2236E-04	0.9973E+0
64.28		1	0.2236E-04	0.9974E+0

A.3 Droplet Conditional Analyses

EXPERIMENT # 21

FLOW PARAMETERS : UGS = 19.5 M/S RC(GAS) = 0.72E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

NO OF DROPLETS	DIAMETER NUMBER DIST (MICRONS)			AXIAL VELOCITY NUMBER DIST (M/S)			LATERAL VELOCITY NUMBER DIST (M/S)			ANGLE VOLUME DIST (DEGREES)			ABS LATERAL VEL NUMBER DIST (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
19	127	131	38	6.7	6.0	1.8	0.38	0.34	2.25	16.5	14.3	11.6	1.9	1.0	1.2	
134	280	270	55	10.7	10.7	2.3	0.56	0.41	2.90	13.0	12.2	9.2	2.5	2.3	1.7	
160	463	466	54	12.9	12.0	3.0	0.70	0.51	2.93	11.0	9.4	8.0	2.4	2.2	1.7	
137	640	636	50	14.0	14.7	3.2	0.63	0.85	2.77	9.5	8.4	6.6	2.3	2.0	1.6	
68	824	822	52	13.8	15.7	3.2	0.47	0.31	2.78	0.5	6.9	6.7	2.3	1.9	1.7	
45	999	1001	40	16.5	16.0	3.4	0.32	0.24	2.76	7.7	6.9	6.0	2.1	2.0	1.9	
29	1174	1164	49	17.2	17.2	2.9	0.56	1.02	2.82	7.0	6.4	5.4	2.4	1.9	1.7	
15	1360	1351	45	17.3	17.1	2.4	0.27	0.26	2.22	6.2	6.6	5.6	2.0	1.9	1.1	
9	1547	1546	47	18.6	18.4	2.6	-0.79	-1.79	3.81	10.3	7.0	7.1	3.2	2.8	1.9	
3	1746	1766	47	17.6	17.0	0.8	-0.68	-1.02	2.10	5.1	6.2	2.6	2.0	1.8	0.6	
2	1931	1870	67	17.4	17.4	0.0	1.53	1.53	0.51	5.5	5.5	1.4	1.5	1.5	0.3	
TOTAL	621	610	555	324	13.8	13.7	4.1	0.53	0.54	2.88	8.0	6.9	6.1	2.4	2.1	1.7

EXPERIMENT # 22

FLOW PARAMETERS : UGS = 17.8 M/S RC(GAS) = 0.65E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

NO OF DROPLETS	DIAMETER NUMBER DIST (MICRONS)			AXIAL VELOCITY NUMBER DIST (M/S)			LATERAL VELOCITY NUMBER DIST (M/S)			ANGLE VOLUME DIST (DEGREES)			ABS LATERAL VEL NUMBER DIST (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
30	139	152	39	7.5	7.3	1.0	0.78	0.88	2.32	14.8	13.9	9.8	2.0	1.9	1.4	
127	284	294	50	11.4	11.2	2.7	0.38	0.39	2.93	11.9	10.9	0.3	2.4	2.2	1.7	
146	461	458	52	12.4	12.0	3.1	0.09	-0.18	2.51	9.7	8.8	6.6	2.1	1.8	1.4	
126	637	638	53	14.0	13.8	2.9	0.34	0.41	2.61	10.8	7.7	6.8	2.1	2.0	1.6	
67	818	814	51	15.4	15.6	2.9	0.16	0.10	2.85	8.5	7.0	4.4	2.3	2.1	1.7	
40	1086	1088	52	16.8	16.4	3.1	0.16	0.53	2.58	7.4	6.4	5.2	2.1	2.0	1.4	
22	1184	1186	52	17.4	17.8	3.6	0.46	-0.00	2.50	7.0	4.9	6.5	1.9	1.3	1.8	
15	1351	1335	50	16.7	16.0	3.0	0.71	0.35	2.78	7.8	6.9	4.8	2.3	2.4	1.6	
2	1571	1528	49	19.5	19.5	0.0	1.06	-2.65	4.23	12.3	9.8	3.7	4.0	3.2	1.1	
2	2070	2066	31	23.4	23.4	0.0	2.65	1.59	1.59	6.1	4.9	2.5	2.6	1.6	1.3	
TOTAL	579	585	539	316	13.4	13.2	4.0	0.27	0.24	2.71	7.8	7.0	6.0	2.2	1.9	1.6

EXPERIMENT # 23

FLOW PARAMETERS : UGS = 15.9 M/S RE(GAS) = 0.58E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

NO OF DROPLETS	DIAMETER NUMBER DIST (MICRONS)			AXIAL VELOCITY NUMBER DIST (M/S)			LATERAL VELOCITY NUMBER DIST (M/S)			ANGLE VOLUME DIST (DEGREES)			ABS LATERAL VEL NUMBER DIST (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
16	132	131	30	6.0	5.9	1.2	0.66	0.53	2.99	18.5	17.5	11.8	2.5	2.1	1.7	
87	288	295	53	9.2	9.1	2.9	0.41	0.17	2.90	15.4	13.3	11.0	2.3	2.4	1.8	
115	451	445	51	11.1	11.2	2.7	0.36	0.21	3.07	12.9	11.2	9.8	2.5	2.2	1.9	
117	641	645	54	13.0	13.1	3.2	0.33	0.66	2.97	10.9	9.4	8.5	2.4	2.3	1.9	
82	806	801	48	13.8	13.8	3.1	0.55	0.14	2.79	9.4	8.5	6.3	2.4	2.3	1.9	
59	1000	1013	52	15.0	14.7	3.7	0.34	0.04	2.95	8.5	7.2	6.4	2.3	1.5	1.9	
19	1196	1201	53	14.5	14.6	2.4	0.66	0.29	2.48	7.5	5.7	6.5	1.9	1.5	1.7	
12	1356	1341	50	16.2	15.5	5.4	0.28	6.11	2.52	7.1	6.2	4.6	2.1	1.5	1.5	
11	1548	1528	60	16.2	15.6	3.0	0.44	0.32	2.59	7.0	3.3	7.2	1.9	1.1	1.8	
3	1753	1778	59	18.2	18.7	3.5	0.19	1.05	3.00	7.5	7.3	4.8	2.5	2.7	1.4	
3	1917	1913	45	16.0	14.5	1.7	-0.70	-1.05	1.31	3.8	4.1	1.5	1.3	1.3	0.4	
3	2161	2157	25	23.3	22.0	1.4	-0.00	-0.00	0.00	1.6	1.4	0.0	0.3	0.3	0.0	
3	2243	2243	30	15.3	14.9	0.5	0.5	0.70	-0.00	1.79	4.9	2.4	4.6	1.5	0.8	1.4
TOTAL	577	731	661	407	12.0	12.7	4.1	0.39	0.19	2.90	7.4	5.6	6.7	2.3	2.0	1.8

EXPERIMENT # 24

FLOW PARAMETERS : UGS = 14.0 M/S RE(GAS) = 0.52E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

NO OF DROPLETS	DIAMETER NUMBER DIST (MICRONS)			AXIAL VELOCITY NUMBER DIST (M/S)			LATERAL VELOCITY NUMBER DIST (M/S)			ANGLE VOLUME DIST (DEGREES)			ABS LATERAL VEL NUMBER DIST (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
19	125	149	54	5.3	5.1	2.1	0.89	1.05	2.84	20.2	20.2	10.7	2.5	2.3	1.7	
80	270	282	49	8.2	7.7	2.8	0.65	0.62	2.74	15.0	12.9	10.6	2.2	1.9	1.7	
110	460	462	54	9.5	9.7	2.8	0.01	-0.03	2.61	13.0	11.0	10.4	2.1	2.0	1.5	
102	643	645	53	11.7	11.4	3.4	0.38	0.30	2.50	10.1	8.1	0.6	2.0	1.9	1.3	
86	820	819	52	13.2	12.9	3.3	0.20	0.36	2.65	9.3	7.7	7.2	2.1	1.7	1.6	
54	992	986	46	13.7	13.7	3.1	0.79	0.76	2.51	8.6	7.0	6.4	2.0	1.7	1.7	
33	1185	1176	54	14.3	14.2	2.6	0.61	0.26	2.52	7.0	7.2	5.0	1.7	1.7	1.1	
20	1372	1370	49	15.0	15.1	2.9	-0.46	-0.90	2.59	8.8	7.6	6.7	2.1	2.0	1.7	
14	1525	1528	50	15.0	14.7	3.3	-0.15	-0.18	2.02	7.2	7.2	5.0	1.9	1.6	1.2	
10	1749	1726	59	14.5	13.8	2.8	0.11	0.18	3.24	10.1	7.6	8.2	2.4	1.0	2.1	
6	1896	1892	55	14.4	15.6	3.3	-0.80	-1.59	3.07	12.6	10.1	8.2	2.8	2.6	1.7	
3	2055	2056	4	16.0	15.8	0.3	-0.35	-0.00	1.31	4.2	3.8	0.4	1.3	1.3	0.9	
10	2266	2273	29	19.3	18.1	3.7	-0.95	-0.53	2.84	7.1	5.0	5.3	2.3	1.4	1.9	
2	2463	2457	12	14.5	14.5	0.0	2.63	2.63	0.53	10.1	10.1	2.5	2.4	2.1	0.5	
TOTAL	554	759	672	453	11.0	11.5	4.3	0.30	0.33	2.60	0.4	7.0	6.6	2.1	1.9	1.6

EXPERIMENT # 25

FLOW PARAMETERS : UGS = 14.1 M/S RE(GAS) = 0.30E+04
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

NO OF DROPLETS	DIAMETER NUMBER DIST. (MICRONS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
30	130	138	39	6.0	6.1	1.5	-0.10	-0.10	2.61	16.5	12.3	13.0	1.9	1.3	1.7	
58	289	299	54	9.1	8.9	2.8	0.37	0.20	2.46	13.0	12.4	8.6	2.1	2.0	1.4	
104	463	469	38	10.5	10.3	3.0	0.20	0.29	2.55	11.0	9.4	8.2	2.0	2.0	1.3	
72	635	633	40	12.5	12.3	2.7	0.58	0.61	2.36	8.6	7.4	6.4	1.9	1.7	1.4	
91	826	827	51	12.8	12.9	3.3	0.49	0.14	2.70	10.0	8.0	8.8	2.1	1.8	1.6	
45	1003	1003	52	13.8	13.7	2.8	0.34	0.10	2.40	7.6	6.5	6.5	1.9	1.7	1.5	
48	1181	1177	44	15.2	15.3	3.8	0.11	0.33	2.65	9.1	7.1	7.0	2.1	2.0	1.5	
25	1352	1351	46	15.5	14.2	3.9	1.60	1.69	2.55	9.0	7.1	7.6	2.4	2.0	1.8	
18	1578	1585	49	17.5	17.5	2.5	0.82	0.53	2.15	6.2	5.6	4.5	1.8	1.8	1.5	
9	1722	1687	41	17.1	18.0	2.0	0.00	-0.18	1.75	5.1	3.7	3.4	1.3	1.1	1.0	
3	1929	1891	58	17.0	16.4	0.7	2.46	3.16	2.63	9.3	9.3	6.0	2.9	2.9	1.7	
4	2075	2053	43	18.5	17.8	3.0	-2.11	-1.58	1.97	6.5	5.6	4.0	2.1	1.6	1.8	
3	2294	2279	51	15.9	14.5	1.0	1.40	2.11	1.79	5.6	5.4	3.0	2.0	2.4	0.9	
2	2431	2400	49	20.8	20.0	0.0	-2.63	-2.63	0.53	5.6	5.6	0.0	2.4	2.1	0.5	
TOTAL	563	762	700	425	12.5	12.3	4.4	0.41	0.32	2.60	7.7	6.2	6.3	2.0	1.8	1.5

EXPERIMENT # 26

FLOW PARAMETERS : UGS = 24.7 M/S RE(GAS) = 0.95E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

NO OF DROPLETS	DIAMETER NUMBER DIST. (MICRONS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	
49	133	135	32	8.4	8.3	2.0	-1.76	-2.01	3.03	18.8	14.9	12.0	3.0	2.5	1.9	
279	281	282	51	12.9	12.8	2.0	-0.60	-0.69	3.20	12.1	10.7	8.4	2.7	2.5	1.9	
194	453	450	50	16.3	16.2	3.0	-0.24	-0.38	3.22	9.5	9.1	6.1	2.7	2.5	1.8	
101	628	622	49	18.6	18.3	3.3	-0.62	-0.55	3.54	9.3	7.4	7.0	2.9	2.4	2.1	
31	806	801	47	20.1	20.2	2.1	-0.71	-0.63	2.97	6.8	5.6	5.1	2.2	1.9	1.7	
13	992	984	57	19.2	20.8	4.2	-1.85	-1.75	3.26	9.0	8.1	5.9	3.0	1.9	2.2	
2	1173	1173	6	20.6	20.6	0.0	-0.50	-0.51	3.51	7.4	7.4	1.9	3.5	3.0	0.8	
4	1320	1308	25	21.0	21.7	2.1	-1.00	-0.50	1.23	3.7	3.7	1.9	1.1	0.5	1.0	
TOTAL	676	423	377	219	15.0	15.0	4.4	-0.61	-0.79	3.26	9.2	7.9	6.6	2.7	2.5	1.9

EXPERIMENT # 27

FLOW PARAMETERS : UGS = 24.5 M/S RE(GAS) = 0.96E+05
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

NO OF DROPLETS	DIAMETER NUMBER DIST. (MICROMS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	
19	148.	160	25.	8.0	7.9	1.8	0.05	1.02	3.54	20.5	21.6	11.6	3.0	3.2	1.8	
150	286	286	49	11.7	11.9	2.8	-1.47	-1.70	2.99	12.9	11.4	9.3	2.7	2.3	1.9	
172	453	449	55	13.0	14.9	3.2	-1.43	-1.71	2.93	10.3	8.8	7.4	2.7	2.4	1.0	
110	634	632	50	16.6	16.5	2.9	-1.76	-2.01	2.87	9.7	8.5	6.3	2.8	2.5	1.8	
69	822	817	53	18.2	18.0	3.4	-1.54	-1.70	2.99	8.9	7.6	6.2	2.8	2.4	1.8	
41	990	964	58	19.9	19.8	3.6	-1.67	-1.75	3.06	0.7	7.1	6.2	2.9	2.4	1.9	
12	1195	1194	57	22.2	23.3	3.7	-1.53	-1.02	2.93	5.8	4.1	4.8	2.6	2.0	2.1	
4	1381	1369	32	19.3	10.7	1.8	-1.53	-2.55	3.42	9.2	8.1	6.0	2.9	2.8	2.0	
6	1536	1528	55	21.3	21.3	3.6	-0.68	-0.51	2.40	5.4	3.1	6.0	1.8	1.0	1.8	
TOTAL	585	551	497	282	15.4	15.2	4.6	-1.51	-1.70	3.00	8.4	6.8	6.3	2.7	2.4	1.8

EXPERIMENT # 28

FLOW PARAMETERS : UGS = 24.7 M/S RE(GAS) = 0.96E+05
 ULS = 0.069 M/S RE(LIQ) = 0.30E+04

NO OF DROPLETS	DIAMETER NUMBER DIST. (MICRONS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	
31	125	124	25	7.1	7.1	1.3	-1.86	-2.27	3.04	22.3	23.0	12.8	3.1	3.1	1.8	
203	291	297	50	12.4	12.1	2.4	-1.34	-1.94	3.10	13.3	12.9	8.7	2.9	2.7	1.9	
175	453	454	54	15.3	15.4	2.8	-1.66	-1.88	3.01	10.7	9.3	7.5	2.9	2.5	2.0	
184	627	622	51	17.8	17.9	3.2	-2.12	-2.35	2.95	9.8	9.4	6.1	3.0	2.7	1.9	
35	797	786	50	19.2	19.1	3.2	-1.65	-1.37	2.30	7.3	5.7	5.3	2.3	2.2	1.4	
0	990	1008	54	20.8	20.8	2.8	-2.40	-2.67	2.43	7.7	7.2	4.3	2.9	2.7	1.6	
9	1209	1215	41	21.8	21.8	3.3	-1.19	-1.42	2.38	7.0	5.7	3.8	2.5	2.0	1.2	
3	1452	1451	6	18.8	17.5	1.5	1.87	0.27	1.51	5.6	2.9	2.9	1.2	0.4	1.3	
TOTAL	570	462	420	226	14.9	14.8	4.4	-1.70	-2.05	3.03	0.3	6.9	6.1	2.9	2.7	1.9

EXPERIMENT # 29

FLOW PARAMETERS UGS = 21.5 M/S RE(GAS) = 0.03E+03
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

NO OF DROPLETS	DIAMETER NUMBER DIST (MICRONS)			AXIAL VELOCITY NUMBER DIST (M/S)			LATERAL VELOCITY NUMBER DIST (M/S)			ANGLE VOLUME DIST (DEGREES)			ABS LATERAL VEL NUMBER DIST (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
16	144	153	34	6.8	6.8	1.8	-0.99	-1.39	3.68	20.5	21.0	14.1	3.0	2.9	2.1	
87	290	300	51	10.9	11.2	2.6	-1.41	-1.90	3.09	14.8	14.7	9.0	2.9	2.7	1.9	
167	466	467	54	14.0	13.6	3.1	-1.30	-1.66	3.28	12.5	11.0	8.3	3.0	2.8	1.9	
145	640	630	53	15.9	15.7	3.2	-1.98	-2.10	3.25	11.4	9.9	7.2	3.2	2.6	2.0	
73	842	847	55	17.4	17.1	3.3	-1.86	-2.00	3.03	9.9	8.7	6.6	2.7	2.3	1.9	
51	1015	1016	46	18.0	18.0	3.1	-1.25	-1.85	3.50	9.0	9.4	5.8	3.3	3.2	1.9	
24	1198	1198	54	19.3	19.2	2.8	-2.21	-3.00	3.20	9.5	9.1	5.5	3.3	3.2	2.0	
11	1360	1366	47	21.9	22.0	4.7	-0.29	-0.13	2.17	4.7	4.3	2.9	1.7	1.7	1.3	
2	1522	1503	24	19.5	19.5	0.0	-1.59	-1.59	0.53	3.8	3.8	1.9	1.6	1.1	0.8	
6	1723	1699	58	20.6	21.0	2.6	-1.32	-1.59	2.10	5.2	3.8	4.8	2.0	1.6	1.6	
TOTAL	585	636	500	310	15.2	15.1	4.5	-1.55	-1.94	3.26	8.9	7.3	6.5	3.0	2.8	1.9

EXPERIMENT # 30

FLOW PARAMETERS UGS = 21.6 M/S RE(GAS) = 0.02E+03
 ULS = 0.067 M/S RE(LIQ) = 0.33E+04

NO OF DROPLETS	DIAMETER NUMBER DIST (MICRONS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
41	130	144	45	7.9	7.9	2.2	-1.22	-0.93	2.87	16.3	13.0	13.2	2.5	2.1	1.8	
187	283	285	53	12.4	12.4	3.0	-1.35	-1.42	2.03	12.0	10.2	8.0	2.6	2.3	1.7	
182	451	443	51	14.8	14.8	2.8	-1.22	-1.77	3.25	11.5	10.7	7.5	3.0	2.6	1.9	
100	631	626	40	16.6	15.9	3.0	-0.98	-0.98	2.90	8.0	7.9	6.6	2.4	2.1	1.8	
49	817	804	54	18.1	18.0	3.1	-1.32	-2.07	3.35	9.6	8.6	5.9	3.1	2.8	1.7	
18	1013	1019	49	20.8	20.5	3.5	-1.12	-0.27	2.93	6.1	5.3	4.3	2.2	1.9	2.0	
6	1198	1161	49	20.7	21.1	1.0	-0.35	-0.00	2.79	5.9	5.3	3.8	2.2	1.9	1.9	
3	1371	1307	51	22.4	21.7	0.8	-2.12	-1.06	2.29	6.5	2.7	4.7	2.2	0.8	2.4	
2	1534	1479	61	19.0	19.0	0.0	-2.12	-2.12	0.00	3.3	3.3	0.0	2.1	2.1	0.3	
TOTAL	580	469	427	230	14.5	14.3	4.3	-1.24	-1.47	3.07	8.4	7.3	6.6	2.7	2.4	1.8

EXPERIMENT # 31

FLOW PARAMETERS UGS = 21.6 M/S RE(GAS) = 0.02E+03
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

NO OF DROPLETS	DIAMETER NUMBER DIST (MICRONS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
30	120	139	39	7.6	7.5	1.7	-1.34	-2.00	2.58	19.1	20.1	12.4	2.6	2.7	1.6	
183	287	289	51	12.1	12.0	2.9	-1.04	-1.39	3.14	13.3	11.7	9.3	2.8	2.5	1.8	
173	456	457	54	14.1	13.9	3.1	-1.12	-1.42	3.11	11.4	9.0	7.7	2.8	2.4	1.8	
101	634	637	47	16.8	16.0	3.5	-1.44	-1.75	3.03	10.1	9.7	6.7	2.8	2.8	1.8	
50	825	819	55	17.8	17.2	3.9	-0.32	-0.44	2.90	7.7	6.9	6.0	2.2	1.8	1.8	
22	1003	1014	51	18.4	18.7	3.4	-0.53	-1.60	3.65	10.0	10.0	5.9	3.1	2.7	1.9	
9	1211	1241	45	18.8	17.7	3.0	-0.79	-3.20	3.10	11.0	11.7	5.9	3.7	3.5	1.7	
2	1351	1308	49	15.4	15.4	0.0	-2.13	-3.73	2.13	10.0	3.3	8.4	2.4	0.3	2.1	
4	1549	1528	48	18.1	18.1	0.0	0.53	0.53	1.19	3.3	3.3	1.7	1.1	1.1	0.4	
TOTAL	576	491	442	251	14.3	14.1	4.3	-1.11	-1.44	3.15	9.1	7.3	6.6	2.8	2.5	1.8

EXPERIMENT # 32

FLOW PARAMETERS UGS = 17.1 M/S RE(GAS) = 0.64E+03
 ULS = 0.121 M/S RE(LIQ) = 0.60E+04

NO OF DROPLETS	DIAMETER NUMBER DIST (MICRONS)			AXIAL VELOCITY NUMBER DIST (M/S)			LATERAL VELOCITY NUMBER DIST (M/S)			ANGLE VOLUME DIST (DEGREES)			ABS LATERAL VEL NUMBER DIST (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
12	143	162	45	6.8	6.9	2.0	-0.97	-1.39	3.25	16.3	11.7	13.3	2.7	2.0	2.0	
60	282	287	53	10.1	10.3	2.9	-0.73	-0.98	2.89	14.2	12.4	9.7	2.4	2.1	1.7	
124	466	464	53	12.4	11.9	3.3	-1.02	-1.30	3.07	12.8	11.2	8.9	2.7	2.5	1.7	
122	640	640	54	14.3	14.0	3.4	-0.55	-0.43	3.12	10.6	9.3	7.4	2.6	2.3	1.8	
84	819	807	55	15.3	14.0	3.7	-0.90	-1.06	3.01	10.3	8.4	7.7	2.6	2.3	1.8	
79	992	991	47	16.6	16.6	2.3	-1.48	-1.70	2.04	8.9	7.9	6.0	2.6	2.3	1.8	
37	1190	1167	48	18.7	19.1	3.1	-0.37	-0.42	2.87	7.4	6.7	4.9	2.4	2.2	1.4	
26	1372	1369	47	18.4	17.4	3.1	-0.41	-0.00	2.65	7.2	6.0	4.2	2.4	2.2	1.4	
10	1520	1503	52	19.4	18.1	3.1	-0.64	-0.53	3.59	7.5	7.0	4.9	2.1	1.7	1.8	
7	1691	1692	26	16.0	16.0	0.0	-3.63	-3.31	1.25	10.3	11.7	4.6	3.5	3.1	1.1	
3	1942	1974	26	19.1	18.4	0.0	-0.00	-0.00	2.40	8.8	10.5	4.8	2.7	3.3	1.5	
7	2100	2145	72	24.3	23.9	2.2	0.76	-0.27	3.39	6.3	4.1	5.2	2.7	1.9	2.4	
TOTAL	500	744	676	383	14.6	14.5	4.5	-0.04	-1.04	3.07	8.2	7.1	6.2	2.6	2.3	1.8

EXPERIMENT # 34

FLOW PARAMETERS : UG5 = 14.3 M/S RE(GAS) = 0.52E+05
UL5 = 0.069 M/S RE(LIQ) = 0.34E+04

NO OF DROPLETS	DIAMETER NUMBER DIST. (MICROMS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	
11	127.	131.	38	6.0	5.6	1.4	0.48	1.03	2.14	20.1	17.3	10.0	2.8	2.2	1.7	
45	297.	307.	49	9.6	9.5	2.5	-0.16	-0.21	3.05	16.1	15.3	11.6	2.4	2.6	1.6	
110	458.	454.	50	11.7	11.4	2.9	-0.87	-1.14	3.13	13.2	11.3	9.4	2.7	2.3	1.8	
115	643.	645.	54	13.4	12.9	3.0	-1.27	-1.40	3.04	11.5	10.6	7.7	2.7	2.5	1.8	
108	817.	820.	52	14.5	14.6	3.0	-0.41	-0.63	3.35	11.0	10.1	7.3	2.8	2.5	1.8	
69	1003.	1007.	52	16.1	15.6	2.8	-0.80	-1.37	3.42	10.8	10.0	6.4	3.0	3.0	1.8	
51	1188.	1192.	57	17.0	17.0	3.5	-1.15	-1.42	3.10	9.5	8.4	6.4	2.8	2.4	1.8	
24	1359.	1351.	54	17.4	16.4	3.0	-0.44	-1.70	3.20	8.8	7.5	6.0	2.7	2.4	1.8	
10	1569.	1580.	56	16.3	16.0	3.9	-1.69	-1.83	2.65	8.7	7.8	5.6	2.6	2.0	1.9	
15	1752.	1775.	51	17.2	18.7	3.5	-0.42	-1.40	3.82	10.3	9.8	5.6	3.2	2.5	1.9	
5	1905.	1913.	43	16.3	14.5	1.8	-1.88	-2.09	2.42	8.7	7.8	3.8	2.7	2.4	1.3	
2	2292.	2292.	0	18.8	18.8	0.0	-1.57	-2.62	1.57	3.5	3.5	1.7	1.6	0.3	1.3	
TOTAL	568	791	739	378	14.0	13.8	4.1	-0.83	-1.23	3.25	9.6	8.4	6.4	2.8	2.5	1.8

EXPERIMENT # 33

FLOW PARAMETERS : UG5 = 17.4 M/S RE(GAS) = 0.64E+05
UL5 = 0.069 M/S RE(LIQ) = 0.34E+04

NO OF DROPLETS	DIAMETER NUMBER DIST. (MICRONS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	
13	129.	144.	41.	6.4	6.3	1.4	-0.89	-2.10	3.71	21.8	23.4	12.3	3.2	3.4	1.8	
99	298.	310.	51.	11.0	10.9	2.6	-1.32	-1.38	2.96	13.9	12.9	9.4	2.7	2.5	1.8	
135	462.	464.	48.	13.3	13.1	2.8	-1.22	-1.72	3.30	13.3	10.8	8.7	3.0	2.7	1.8	
126	647.	656.	55.	15.2	14.7	3.2	-0.69	-1.18	3.57	11.4	10.3	7.5	3.0	2.8	1.9	
83	833.	835.	54.	16.3	16.2	3.3	-0.47	-0.84	3.45	10.5	10.0	6.6	3.0	2.9	1.8	
42	999.	984.	58.	17.7	17.4	3.7	-1.28	-1.73	2.82	8.5	8.0	5.4	2.6	2.5	1.6	
24	1179.	1161.	56.	18.6	18.9	3.1	-0.61	-1.05	3.35	8.9	8.5	5.1	2.9	2.6	1.7	
17	1361.	1360.	60.	18.1	19.0	3.5	-0.43	-0.26	3.66	9.9	10.0	6.7	3.0	2.8	2.1	
3	1542.	1558.	51.	16.5	16.3	0.3	4.20	6.04	2.97	12.7	16.3	7.8	4.3	6.0	2.9	
4	1670.	1674.	38.	21.5	22.1	1.2	1.05	1.05	0.74	2.7	2.4	1.6	0.9	0.8	0.6	
3	1885.	1870.	29.	21.5	20.9	1.1	-0.00	-0.53	1.29	3.4	3.6	1.8	1.1	1.1	0.6	
3	2080.	2072.	40.	18.7	15.8	3.2	-0.00	-0.00	4.29	11.5	12.7	7.5	3.6	5.0	2.4	
TOTAL	573	647.	588	831.	14.5	14.2	4.3	-0.91	-1.20	3.37	9.2	7.8	7.1	2.9	2.7	1.8

EXPERIMENT # 40

FLOW PARAMETERS : UCS = 24.6 M/S RE(GAS) = 0.94E+03
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

NO OF DROPLETS	DIAMETER NUMBER DIST. (MICRONS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
32	120	118	44	6.7	6.6	1.9	-0.12	-0.26	2.66	17.9	14.9	10.6	2.2	2.0	1.3	
134	281	284	58	10.3	10.3	2.9	-0.23	-0.21	2.72	12.0	10.9	9.7	2.1	1.6	1.7	
122	438	460	53	12.9	13.0	2.9	0.12	-0.00	3.19	11.4	10.8	7.9	2.6	2.3	1.9	
112	631	627	52	13.5	13.5	3.3	-0.32	-0.29	2.47	8.2	7.0	6.2	2.0	1.8	1.3	
64	820	826	49	14.3	14.2	3.6	0.46	0.15	2.37	7.7	5.6	6.9	1.9	1.4	1.6	
36	976	996	51	14.2	14.9	3.5	-0.21	-0.29	2.65	8.7	7.9	6.5	2.1	1.9	1.6	
26	1173	1173	41	13.9	13.4	4.0	-0.20	-0.35	2.16	6.5	5.4	4.7	1.7	1.4	1.3	
8	1366	1369	44	14.0	12.7	3.2	0.79	1.59	2.17	7.3	6.9	4.5	2.0	2.1	0.9	
9	1549	1546	49	13.1	12.5	2.7	-0.12	-0.35	2.08	7.1	5.2	5.4	1.6	1.3	1.3	
3	1756	1778	49	13.7	12.2	2.1	0.44	1.03	3.25	10.7	8.6	7.1	2.7	2.0	1.9	
5	1915	1901	63	13.2	11.1	2.9	-0.00	-1.06	2.22	7.9	7.7	2.6	2.1	2.0	0.9	
2	2072	2041	37	12.0	12.0	0.0	1.59	1.59	0.53	5.2	3.4	3.4	1.3	1.1	0.5	
2	2316	2273	49	10.1	10.1	0.0	1.06	-0.53	2.12	8.6	3.4	6.9	1.9	1.1	1.1	
TOTAL	577	590	517	382	12.3	12.1	4.1	-0.08	-0.27	2.77	7.9	7.1	6.1	2.2	1.9	1.7

EXPERIMENT # 41

FLOW PARAMETERS : UCS = 24.4 M/S RE(GAS) = 0.95E+03
 UL5 = 0.121 M/S RE(LIQ) = 0.60E+04

NO OF DROPLETS	DIAMETER NUMBER DIST. (MICRONS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
30	116.	124.	44.	6.9	6.5	2.0	-0.17	0.11	3.14	18.7	18.7	12.7	2.4	1.9	1.9	
140	283	284	52	11.4	11.4	2.5	-0.04	-0.18	3.23	12.4	10.7	9.2	2.6	2.3	1.9	
133	454	458	51	12.9	12.9	3.0	-0.28	-0.10	2.78	10.5	9.6	7.6	2.6	2.2	1.5	
86	646	643	34	13.9	14.0	2.9	-1.04	-1.14	2.38	8.7	7.9	7.0	2.1	1.9	1.5	
49	806	801	55	13.9	13.1	3.5	-0.24	-0.13	2.57	8.6	7.9	6.0	2.0	1.6	1.6	
36	1002	1005	50	14.6	14.0	2.9	-0.12	-0.04	2.70	8.4	6.4	6.1	2.0	1.6	1.4	
20	1170	1173	45	15.3	14.8	3.6	0.14	-0.11	1.83	3.7	4.6	4.3	1.4	1.1	1.1	
13	1386	1390	54	14.0	14.2	2.7	-0.49	-0.13	2.05	7.5	6.7	5.9	1.8	1.7	1.3	
6	1548	1540	46	13.1	13.1	1.5	2.10	2.10	2.35	11.0	9.2	5.5	2.7	2.1	1.5	
3	1713	1705	50	14.9	11.3	4.0	-1.03	-0.24	1.49	3.3	2.8	5.2	1.1	0.4	1.2	
TOTAL	538	546	468	340	12.6	12.5	3.8	-0.31	-0.32	2.88	8.1	7.1	6.5	2.3	2.0	1.7

EXPERIMENT # 42

FLOW PARAMETERS : UCS = 24.6 M/S RE(GAS) = 0.94E+03
 UL5 = 0.121 M/S RE(LIQ) = 0.65E+04

NO OF DROPLETS	DIAMETER NUMBER DIST. (MICRONS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
20	139.	141	33.	7.4	7.3	2.0	-0.21	-0.00	3.11	17.1	12.5	14.2	2.4	1.9	1.9	
117	288	299	34	10.9	11.1	2.6	-0.48	-0.46	2.96	13.0	11.7	9.6	2.5	2.4	1.8	
174	453	452	52	13.1	12.9	3.0	-0.63	-0.91	3.12	11.5	10.8	7.7	2.6	2.4	1.8	
124	632	629	54	13.2	13.3	2.4	-0.33	-0.33	3.15	9.4	8.2	7.2	2.5	2.2	1.9	
77	815	808	50	16.5	16.2	3.2	-0.84	-0.89	3.96	10.5	9.1	8.0	2.9	2.7	1.9	
44	1000	995	54	18.3	18.1	2.7	0.56	0.40	2.82	7.3	5.8	5.3	2.3	2.2	1.7	
18	1171	1161	49	18.4	18.4	1.9	-0.30	-0.89	3.63	9.2	10.0	6.3	3.0	2.9	2.0	
10	1359	1338	57	20.9	20.9	1.9	-2.02	-2.30	2.62	8.7	7.8	4.8	3.0	2.7	1.6	
3	1542	1546	15	20.7	19.9	0.9	-2.83	-5.31	5.08	13.9	11.7	5.7	5.6	5.0	1.6	
TOTAL	590	584	534	288	14.2	14.1	4.1	-0.53	-0.80	3.21	9.6	8.9	6.6	2.6	2.3	1.8

EXPERIMENT # 43

FLOW PARAMETERS : UCS = 24.8 M/S RE(GAS) = 0.94E+03
 UL5 = 0.034 M/S RE(LIQ) = 0.17E+04

NO OF DROPLETS	DIAMETER NUMBER DIST. (MICRONS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	MEAN	MEDIAN	ST. DEV	
21	146	148	23	8.4	8.5	1.3	-1.07	-1.61	3.20	14.9	12.9	9.9	2.6	1.9	2.0	
137	289	292	50	12.7	12.5	2.8	-1.32	-1.39	2.00	11.4	10.8	7.9	2.5	2.3	1.8	
208	452	450	53	13.5	13.7	3.4	-1.14	-1.16	3.18	10.4	8.7	7.7	2.8	2.4	1.9	
118	632	629	55	17.4	17.4	3.2	-1.12	-1.43	3.03	9.0	8.4	6.2	2.7	2.4	1.8	
34	811	811	52	19.2	20.1	3.6	-1.89	-2.38	3.09	9.3	8.9	6.4	3.0	3.1	1.9	
14	979	978	47	18.6	10.7	3.7	-1.30	-1.27	2.54	7.0	6.7	3.9	2.3	2.3	1.4	
7	1179	1155	61	19.4	19.5	3.4	-0.87	-0.00	3.24	8.2	4.9	6.8	2.6	1.8	2.1	
2	1424	1424	0	25.5	25.5	0.0	-2.04	-2.55	1.02	4.0	2.7	2.7	1.8	1.0	1.0	
TOTAL	587	494	456	221	15.5	15.4	4.3	-1.27	-1.46	3.07	8.6	7.3	6.4	2.7	2.4	1.8

EXPERIMENT # 44

FLOW PARAMETERS : UGS = 17.7 M/S RE(GAS) = 0.43E+05
 ULS = 0.034 M/S RE(LIQ) = 0.17E+04

NO OF DROPLETS	DIAMETER NUMBER DIST (MICRONS)			AXIAL VELOCITY NUMBER DIST (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)					
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV			
11	139	162	34	4	4	5 0	1	4	-0 67	-0 66	1 44	17 8	12 9	12 7	1 2	0 9	0 9	
99	291	296	40	0	3	0 1	2	4	-0 62	-0 68	2 59	14 0	11 9	11 1	2 1	1 8	1 6	
130	465	471	51	10	10	10 8	2	7	-1 26	-1 15	2 30	11 7	9 5	9 2	2 2	1 9	1 7	
119	631	625	53	12	5	12 2	3	9	-1 20	-1 19	2 35	9 8	8 0	7 5	2 1	1 9	1 8	
91	829	820	52	14	4	15 0	3	4	-1 00	-1 26	2 74	9 9	8 3	7 4	2 4	2 0	1 6	
37	992	903	49	14	4	15 0	3	4	-1 09	-0 97	2 20	0	6	5 3	6 7	1 9	1 7	
32	1176	1177	50	13	2	14 5	3	8	-1 38	-0 79	2 17	7 8	5 9	6 3	2 0	1 4	1 8	
15	1345	1329	45	13	1	15 4	3	2	-0 36	-0 66	2 55	7 3	6 4	5 6	2 0	1 3	1 6	
11	1584	1595	47	16	0	16 1	2	1	-0 76	-1 05	3 13	9 3	8 9	6 2	2 4	2 8	1 7	
4	1763	1778	42	16	6	17 0	1	6	-1 32	-0 53	1 73	5 9	4 0	4 0	1 3	0 5	1 3	
2	1907	1846	67	17	5	17 5	0	0	-2 64	-2 64	0 53	7 9	7 9	2 0	2 4	2 1	0 3	
2	2310	2261	55	17	3	17 3	0	0	-4 22	-6 84	3 16	11 9	7 9	5 9	4 2	1 6	2 9	
TOTAL	577	676	602	350	12	2	11 9	4	0	-1 12	-1 12	2 49	0 7	6 8	6 9	2 1	1 8	1 6

EXPERIMENT # 45

FLOW PARAMETERS : UGS = 17.5 M/S RE(GAS) = 0.63E+05
 ULS = 0.121 M/S RE(LIQ) = 0.64E+04

NO OF DROPLETS	DIAMETER NUMBER DIST (MICRONS)			AXIAL VELOCITY NUMBER DIST (M/S)			LATERAL VELOCITY NUMBER DIST (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
4	168	175	16	5.4	5.7	1.0	-1.20	-1.45	1.43	14.7	11.8	7.5	1.7	1.4	0.8	
35	289	287	46	7.0	7.6	2.0	-0.52	-0.10	2.61	14.0	13.7	10.2	2.1	2.1	1.5	
77	472	480	49	10.4	10.3	2.5	-1.19	-1.08	2.43	11.6	9.4	9.2	2.1	1.8	1.7	
103	637	645	54	12.3	12.3	3.2	-1.07	-1.02	2.28	9.9	7.1	8.8	2.0	1.4	1.5	
94	815	812	52	12.8	12.6	2.8	-0.77	-1.10	2.93	10.6	9.2	7.6	2.4	2.0	1.8	
82	1003	1002	53	14.3	14.2	2.9	-0.89	-0.87	2.37	8.5	7.0	6.0	2.0	1.7	1.5	
54	1185	1179	49	15.1	15.4	2.9	-0.77	-0.89	2.54	7.8	6.2	6.4	2.1	1.8	1.6	
54	1373	1381	51	14.0	14.6	2.6	-0.73	-0.96	2.90	9.0	8.4	6.5	2.4	2.0	1.9	
26	1571	1580	46	16.2	15.7	3.0	-0.89	-1.03	2.25	6.9	5.6	5.3	2.0	1.9	1.4	
13	1727	1717	47	16.3	15.9	2.8	-0.48	-0.40	2.60	8.9	7.4	6.6	2.2	2.1	1.3	
5	1928	1925	33	16.3	16.7	2.7	-1.35	-2.41	2.41	7.8	7.8	4.8	2.3	2.4	1.4	
5	2099	2084	55	17.1	16.6	0.9	-1.34	-1.93	2.48	9.0	9.8	4.6	2.7	3.1	1.3	
TOTAL	547	701	831	417	13.2	13.1	3.9	-0.87	-0.96	2.55	8.5	7.4	6.3	2.1	1.8	1.6

EXPERIMENT # 46

FLOW PARAMETERS : UGS = 17.7 M/S RE(GAS) = 0.62E+05
 ULS = 0.034 M/S RE(LIQ) = 0.19E+04

DIAMETER NUMBER DIST. (MICRONS)				AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
NO OF DROPLETS	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
12	120	134	47	3.2	3.3	1.2	0.53	-0.00	3.52	38.3	44.0	18.8	3.1	3.2	1.9	
70	293	306	49	7.7	7.5	2.3	0.23	0.10	3.39	20.0	17.8	13.7	2.9	2.6	1.9	
76	456	464	50	9.5	9.5	2.0	0.08	-0.35	2.98	14.2	11.6	11.1	2.4	2.1	1.8	
92	641	632	54	10.9	10.9	3.1	0.12	-0.53	3.06	13.5	13.2	8.8	2.5	2.2	1.7	
66	820	813	57	12.4	12.2	3.1	0.58	0.53	3.02	11.7	10.6	8.2	2.5	2.2	1.8	
58	909	903	48	12.6	12.5	2.8	0.22	0.13	3.44	13.2	11.5	9.6	2.9	2.6	2.0	
52	1177	1165	50	13.9	13.8	3.3	0.73	0.79	2.90	10.3	8.4	8.0	2.4	2.0	1.8	
39	1377	1376	54	12.9	12.9	3.3	0.25	-0.24	3.05	11.4	7.9	9.5	2.4	1.7	1.9	
22	1541	1513	50	13.6	13.1	4.0	1.15	1.74	3.41	12.2	10.0	8.4	2.9	2.3	2.0	
10	1722	1695	56	16.0	16.3	2.9	0.29	-0.00	2.23	7.1	5.9	5.3	1.9	1.9	1.3	
6	1917	1907	53	14.0	13.9	1.8	-1.59	-1.59	2.72	10.3	8.8	8.9	2.4	2.1	2.0	
10	2130	2135	25	14.3	14.4	3.5	-0.53	-1.06	3.58	12.7	7.7	11.3	3.0	2.6	2.1	
9	2284	2279	48	15.2	15.5	3.5	-2.12	-1.85	3.12	12.5	9.9	8.8	3.1	2.0	2.1	
TOTAL	330	865	774	491	11.5	11.3	4.1	0.24	-0.06	3.21	11.2	8.7	9.2	2.6	2.2	1.9

EXPERIMENT # 47

FLOW PARAMETERS : UGS = 17.5 M/S RE(GAS) = 0.62E+05
 ULS = 0.121 M/S RE(LIQ) = 0.62E+04

NO OF DROPLETS	DIAMETER NUMBER DIST. (MICRONS)			AXIAL VELOCITY NUMBER DIST. (M/S)			LATERAL VELOCITY NUMBER DIST. (M/S)			ANGLE VOLUME DIST. (DEGREES)			ABS LATERAL VEL NUMBER DIST. (M/S)			
	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	MEAN	MEDIAN	ST DEV	
8	86	67	46	2.7	1.8	1.6	1.03	2.07	3.10	37.5	37.5	18.1	2.8	2.6	1.6	
50	289	299	51	8.3	8.2	2.7	-0.10	-0.37	3.10	17.0	14.2	16.0	2.5	2.2	1.8	
60	459	460	51	10.0	10.0	2.8	-0.38	-0.14	3.20	15.2	13.2	11.2	2.6	2.1	1.8	
85	640	635	54	11.9	12.1	3.3	0.09	-0.00	3.96	16.6	14.2	11.3	2.3	2.9	2.0	
97	854	817	52	12.9	12.7	3.1	0.09	-0.30	3.29	11.9	11.0	8.4	2.7	2.6	1.9	
44	1002	780	52	12.9	12.9	2.8	-0.29	-0.29	3.74	13.3	12.2	6.9	3.1	3.0	2.2	
69	1200	1220	55	13.1	13.0	3.5	-0.61	-1.19	3.19	11.0	9.6	6.9	2.7	2.4	1.8	
20	1366	1366	50	14.1	13.7	2.9	-0.22	-0.17	3.24	10.9	8.3	7.6	2.8	2.3	2.0	
17	1754	1745	46	17.1	17.0	4.7	-0.97	-1.03	3.24	11.3	8.8	9.0	2.9	2.6	1.9	
12	1902	1894	41	14.9	14.7	3.6	0.47	0.77	3.42	12.5	13.8	6.5	2.9	2.0	1.7	
7	2100	2100	34	17.1	15.9	3.0	-0.89	-1.29	1.07	6.1	5.8	3.5	1.8	1.8	1.0	
5	2275	2279	43	14.4	14.3	1.4	0.41	-0.00	2.41	7.5	7.5	3.2	2.1	2.2	1.2	
2	2414	2400	12	14.0	14.0	0.0	1.55	1.55	0.52	3.0	3.0	2.3	1.5	1.5	0.3	
2	2652	2591	67	19.5	19.5	0.0	0.52	-0.52	1.55	5.0	5.0	2.5	1.8	1.5	0.5	
TOTAL	322	914	834	476	12.7	12.6	4.3	-0.16	-0.35	3.43	10.4	8.3	8.0	2.8	2.5	1.9

Appendix B

FORTRAN 77 Listings of Computer Codes

B.1 Listing of Program DIASIM Used for the Simulation of Droplet-Laser Interference

```

C      PROGRAM DIA5M2
C      DIAMETER SIGNAL SIMULATION
C
C      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C      DIMENSION AMP(300),VELA(10),VELR(10)
C      DIMENSION TIMIN(10),TIMOUT(10)
C      COMMON DIAMP(10),XP(10),ZP(10)
C      NUMP=3
C      XP(1)=14000.
C      XP(2)=15000.
C      XP(3)=16000.
C      DIAMP(1)=50.
C      DIAMP(2)=100.
C      DIAMP(3)=70.
C      VELA(1)=5.0
C      VELA(2)=5.
C      VELA(3)=5.0
C      VELR(1)=0.
C      VELR(2)=0.
C      VELR(3)=0.
C      FREQ=1.
C      DT=1.0
C      DDT=6.25D-03
C      NDT=DT/DDT
C      VELG=FREQ*49.9
C      Z0=0.
C      DZ=VELG*DDT
C      WRITE(10,1000) ((XP(I),DIAMP(I),VELA(I),VELR(I)),I=1,NUMP)
C      WRITE(10,*)
C      AIPH=0.0
C      ZP(1)=3000.0
C      ZP(2)=3000.0
C      ZP(3)=3000.0
C      NSC=30
C      DO 90 JT=1,NSC
C      DO 80 LT=1,NDT
C      Z00=Z0+DZ
C      Z0=(Z00/50.-DINT(Z00/50.))*50.
C      DO 30 J=1,24
C      Z5=Z0+50.*(J-1)
C      AMPH=0.000
C      CALL RAYSIM(NUMP,Z5,AMPH)
C      IF (JT.NE.1) AIPH=AIPH+AMPH
30  CONTINUE
80  CONTINUE
90  CONTINUE
      SCF=AIPH/(NSC-1)
      ZP(1)=750.
      ZP(2)=890.
      ZP(3)=1010.
      TIMES=(ZP(NUMP)-600.0+37.5+0.75*DIAMP(NUMP))/VELA(NUMP)
      TIME=(1200.+DIAMP(NUMP)*.5-ZP(NUMP))/VELA(NUMP)
      T0=TIME
      MAXT=TIMES/DT
      DO 900 JT=1,MAXT
      PM=0.
      DO 800 LT=1,NDT
      AIPH=0.
      NP=0
      NP=0
      Z00=Z0+DZ
      Z0=(Z00/50.-DINT(Z00/50.))*50.
      DO 200 N=1,NUMP
      XP(N)=XP(N)-DDT*VELR(N)
      ZP(N)=ZP(N)-DDT*VELA(N)
      IF ((ZP(N)-DIAMP(N)*.5).GT.637.5) TIMIN(N)=TIME
      IF ((ZP(N)+DIAMP(N)*.5).GT.562.5) TIMOUT(N)=TIME
200  CONTINUE
      DO 300 J=1,24
      Z5=Z0+50.*(J-1)
      AMPH=0.000
      CALL RAYSIM(NUMP,Z5,AMPH)
      AIPH=AIPH+AMPH
300  CONTINUE
      PM=PM+AIPH

```

```

      TIME=TIME+DDT
800  CONTINUE
      AMP(JT)=PM/SCF
      WRITE(10,2000) JT*DT,AMP(JT),ZP(1),ZP(2),ZP(3)
900  CONTINUE
1000 FORMAT(' XP=',F6.0,' DIAM=',F6.0,' VEL=',F4.0,' VELR=',F4.0)
2000 FORMAT(F10.2,F7.4,F6.0,F6.0,F6.0)
      STOP
      END

```

C
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```

      SUBROUTINE RAYSIM(NUMP,Z1,AMPH)

```

C
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```

      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(2048),Z(2048),GAMA(2048),AMPR(2048)
      DIMENSION XI(2),ZI(2),DISTO(2)
      COMMON DIAMP(10),XP(10),ZP(10)

```

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```

      INTERMEDIATE DATA

```

```

      XS=50000.
      DISTMA=XS
      PI=4.*DATAN(1.0D0)
      AMPR(1)=1.
      AMPH=0.
      X(1)=0.
      Z(1)=Z1
      GAMA(1)=0.

```

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```

      END OF INTERMEDIATE DATA
      BEGINNING OF SUBPROGRAM

```

```

      DO 700 I=1,10
      IF(JFLAG.EQ.(2**I*.25)) GO TO 800
      JFLAG=0
      JMIN=2**I
      JMAX=2**((I+1)-1)
      DO 650 J=JMIN,JMAX
      GAMA(J)=0.0
      AMPR(J)=0.0
650  CONTINUE
      DO 600 J=2**((I-1),2**I-1
      Z5=101.
      IF(AMPR(J).GT.0.0) GO TO 100
      JFLAG=JFLAG+1
      GO TO 600
100  DISTH=DISTMA
      KM=0
      DO 200 K=1,NUMP
      KI=K
      CALL INTERC(X(J),Z(J),GAMA(J),KI,A,B,XI(1),XI(2),IG)
      IF(IG.EQ.2.OR.IG.EQ.1) GO TO 200
      ZI(1)=A*XI(1)+B
      ZI(2)=A*XI(2)+B
      DISTO(1)=DSQRT((X(J)-XI(1))**2+(Z(J)-ZI(1))**2)
      DISTO(2)=DSQRT((X(J)-XI(2))**2+(Z(J)-ZI(2))**2)
      KM=2
      IF(DISTO(1).LE.DISTO(2)) KM=1
      DIST=DISTO(KM)
      IF(DIST.GT.DISTH) GO TO 200
      DISTH=DIST
      KM=K
      XR=XI(KM)
      ZR=XI(KM)+B
200  CONTINUE
      IF(KMIN.EQ.0.1) GO TO 300
      JD=2*J
      JDP1=JD+1
      X(JDP1)=XR
      Z(JDP1)=ZR
      XJM=X(J)-XR
      ZJM=Z(J)-ZR
      XPM=XP(KMIN)-XR
      ZPM=ZP(KMIN)-ZR
      TETAJ=(XJM*XPM+ZJM*ZPM)**2
      TETAL=(XJM*XJM+ZJM*ZJM)*(XPM*XPM+ZPM*ZPM)

```

```

TETA=DSQRT(TETAJ/TETAL)
IF (TETA.GT.1.0.AND.TETA.LT.1.1) TETA=1.
TETAI=DABS(DARCOS(TETA))
TETA0=DABS(DARSIN(DSIN(TETAI)/1.33))
G1=(Z(J)-ZP(KMIN))/(X(J)-XP(KMIN))
CALL INTERC(X(J),Z(J),G1,KMIN,AD,BD,XC1,XC2,JG)
XC=XC1
IF((DABS(XC2-X(J))) .LT. (DABS((X(J)-XP(KMIN)))) XC=XC2
ZC=AD*XC+BD
SIGN=1.
IF((ZP(KMIN)-ZC)*(XR-XC) .LT. 0.0) SIGN=-1.
BETA=GAMA(J)+PI+SIGN*2*TETAI
GAMA(JDP1)=BETA-DINT(BETA*.5/PI)*2*PI
IF(GAMA(JDP1) .LT. 0.0) GAMA(JDP1)=GAMA(JDP1)+2*PI
PHI=PI-TETAI-TETA0
G2=GAMA(JDP1)+SIGN*PHI
CALL INTERC(XR,ZR,G2,KMIN,AR,BR,XD1,XD2,LG)
XD=XD1
IF(DABS(XR-XD1) .LE. 1E-1) XD=XD2
ZD=AR*XD+BR
X(JD)=XD
Z(JD)=ZD
CSI=G2+SIGN*(TETAI-TETA0)
GAMA(JD)=CSI-DINT(CSI*.5/PI)*2*PI
IF(GAMA(JD) .LT. 0.0) GAMA(JD)=GAMA(JD)+2*PI
ANGP=TETAI+TETA0
ANGM=TETAI-TETA0
AMPR(JD)=1.
AMPR(JDP1)=0.
IF(ANGP .LE. 0.0) GO TO 600
R=DSQRT((DTAN(ANGM)*DCOS(TETAI)/DTAN(ANGP))**2+
& (DSIN(ANGM)*DSIN(TETAI)/DSIN(ANGP))**2)
AMPR(JDP1)=AMPR(J)*R
T=4*(DCOS(TETAI)/(DSIN(2.*TETA0)/DSIN(2.*TETAI)+1))**2
& +4*(DSIN(TETAI)/(DTAN(TETAI)/DTAN(TETA0)+1))**2
T=DSQRT(T*(4*(DCOS(TETA0)/(DSIN(2.*TETAI)/DSIN(2.*TETA0)+1))**2
& +4*(DSIN(TETA0)/(DTAN(TETA0)/DTAN(TETAI)+1))**2)))
AMPR(JD)=AMPR(J)*T
GO TO 600
300 IF(DCOS(GAMA(J)) .LE. 0.) GO TO 400
Z5=A*X5+B
IF(Z5 .LE. 562.5 .OR. Z5 .GT. 637.5) GO TO 400
AMPH=AMPH+AMPR(J)**2
WRITE(09,3000) X(J),Z(J),GAMA(J),AMPH,Z5,XP(1),ZP(1)
3000 FORMAT(2F6.0,F4.2,E12.3,3F6.0)
400 IF (J.EQ.1) GO TO 800
AMPR(J)=0.
600 CONTINUE
700 CONTINUE
800 RETURN
END

```

C
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C
C

SUBROUTINE INTERC(X,Z,G,K,A,B,X1,X2,IG)

```

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
COMMON DIAMP(10),XP(10),ZP(10)
IG=0
A=DTAN(G)
B=Z-A*X
CA=A*A+1.
CBI=B-ZP(K)
CB=2.*(A*CBI-XP(K))
CC=CBI*CBI-DIAMP(K)*DIAMP(K)*.25+XP(K)*XP(K)
DEL=CB*CB-4*CA*CC
IF(DEL.GT.0.) GO TO 100
IG=1
RETURN
100 BOTA=-CB/CA*.5
DELOTA=DSQRT(DEL)*.5/CA
X1=BOTA-DELOTA
X2=BOTA+DELOTA
IF((X1-X) .LE. 1E-1 .OR. (X2-X) .LE. 1E-1) IG=2
RETURN
END

```

B.2 Listing of Program STAT4 Used for the Statistical Analysis of Experimental Results

```

C      PROGRAM STAT4
C
C      A STATISTICAL ANALYSIS IS PERFORMED ON EXPERIMENTAL
C      DATA OBTAINED DURING THE MEASUREMENT OF DROPLET SIZE AND
C      VELOCITIES IN ANNULAR FLOW. EACH DATA POINT IS A VECTOR
C      WITH FIVE COMPONENTS : DROPLET DIAMETER      - DIAM
C      DROPLET AXIAL VELOCITY      - VE
C      DROPLET LATERAL VELOCITY    - VER
C      DROPLET ANGLE                - ANGL
C      DROPLET ABS LAT VEL         - PAST
C
C      THE PROGRAM OUTPUT IS CONTROLLED BY IFOUT.
C      IF IFOUT(1)=1      - PRINT SORTED DATA FILE.
C      IFOUT(2)=1      - PRINT GLOBAL STATISTICAL ANALYSIS.
C      IFOUT(3)=1      - PRINT COND. STATISTICAL ANALYSIS.
C      IFOUT(4)=1      - PRINT PLOT FILE FOR FURTHER PROCESSING.
C
C      DIMENSION DIA(1024),VE(1024),VER(1024),RIT(1024)
C      DIMENSION RHMM(5),FN(80),CM(40)
C      DIMENSION ANGL(1024),PAST(1024)
C      DIMENSION DI(1024),V(1024),VR(1024),ANG(1024),PS(1024)
C      DIMENSION QTN(15),QTV(15),IOUT(4),IFOUT(4)
C      CHARACTER CCL,QTN*6,QTV*6
C      COMMON /DIARNG/ DVMN,DVMX,WGT(1024)
C      COMMON NEXP,WG,UG5,REG,WL,UL5,REL,DELP,I01,I02,I03,I04
C      COMMON NQ,NSTAT,CSTAT(20,19)
C      DATA IOUT/0,0,0,0/,IFOUT/0,1,1,1/
C      DATA QTN/'NUM.Q1','NUM.Q2','NUM.Q3','NUM.Q4','NUM.Q5',
C      &          'NUM.Q6','NUM.Q7','NUM.Q8','NUM.Q9','NUM.10',
C      &          'NUM.11','NUM.12','NUM.13','NUM.14','NUM.15'/
C      DATA QTV/'VOL.Q1','VOL.Q2','VOL.Q3','VOL.Q4','VOL.Q5',
C      &          'VOL.Q6','VOL.Q7','VOL.Q8','VOL.Q9','VOL.10',
C      &          'VOL.11','VOL.12','VOL.13','VOL.14','VOL.15'/
C
C      C      INITIALIZATION OF PROGRAM PARAMETERS AND CONSTANTS.
C
C      CCL=CHAR(12)
C      I01=5
C      I02=7
C      I03=10
C      I04=6
C      NJ=0
C      IFL1=0
C      CRMAX=30.
C      NQUART=15
C      SMIN=10.
C      DMX=2750
C      VMX=8.0
C      DMN=0.0
C      DVMN=DMN
C      AVMN=0.0
C      AMN=0.0
C      TMN=0.0
C      DELP=0.0
C      PIC=45./ATAN(1.)
C      OPEN(UNIT=I02,STATUS='OLD',ACCESS='DIRECT',RECL=80)
C
C      INPUT OF EXPERIMENTAL FILES TO BE PROCESSED FROM
C      FILE STAT DATA C.
C
C      WRITE(I01,*)' INPUT EXPERIMENT NUMBER ,(**) '
C      READ(I01,1100)NEXP
C      NF=1
C      NREC=1
C      DIAMAX=0.0
C      VEMAX=0.0
C      VERMAX=0.0
C      ANGMAX=0.0
C      PASMAY=0.0
C      SUMD=0.0
C      SUMS=0.0
C      SUMV=0.0

```



```

      PAST(LSP1)=RIN4
      END IF
40  CONTINUE
50  CONTINUE
C
C      COMPUTE THE ANGLE FOR EACH DATA POINT.
C
60  DO 70 L6=1,NJ
      ANGL(L6)=ABS(ATAN(VER(L6)/VE(L6))*PIC)
      WGT(L6)=DIA(L6)**3
      IF (ANGL(L6).GT.ANGMAX) ANGMAX=ANGL(L6)
70  CONTINUE
C
C      OUTPUT A FULL LISTING OF THE DATA VECTORS IF IFOUT(1)=1.
C
      WRITE(IO4,8500) CCL,NEXP,UGS,REG,ULS,REL
      WRITE(IO4,5000) CCL
      IF (IFOUT(1).EQ.1) THEN
        DO 75 L6=1,NJ
          IF (L6.EQ.((L6-1)/40)*40+1)
            &      WRITE(IO4,3000) CCL,NEXP,(L6-1)/40+1,UGS,REG,ULS,REL,NJ
          WRITE(IO4,4000)L6,DIA(L6),VE(L6),VER(L6),ANGL(L6),
75  CONTINUE
          WRITE(IO4,5000) CCL
        END IF
C
C      A GLOBAL STATISTICAL ANALYSIS IS MADE FOR EACH COMPONENT OF
C      EXPERIMENTAL RANDOM DATA VECTOR.
C
      NQ=1
      DMX=DIAMAX
      DVMX=DMX**3
      AVMX=VEMAX
      VMX=ABS(VERMAX)
      VMN=-ABS(VERMAX)
      AMX=ANGMAX
      TMX=PA5MAX
      M=15
      CSTAT(1,1)=NJ
      IF (IFOUT(2).EQ.1) THEN
        IOUT(1)=1
        IOUT(2)=1
        IOUT(3)=1
      END IF
      IF (IFOUT(4).EQ.1) THEN
        WRITE(IO3,*) NEXP,UGS,ULS
        WRITE(IO3,*) NJ,D10,D20,D30,D21,D31,D32
        IOUT(4)=1
      END IF
      CALL STS(IOUT,NJ,DIA,M+5,DMX,DMN,'DIAMETER', 'NUMBER',CM,FN)
      CALL STS(IOUT,NJ,VE,M-5,VMX,VMN,'AXIAL VELOC', 'NUMBER',CM,FN)
      CALL STS(IOUT,NJ,VER,M-5,VHX,VMN,'LATERAL VEL', 'NUMBER',CM,FN)
      CALL STS(IOUT,NJ,ANGL,M+5,AMX,AMN,'ANGLE', 'VOLUME',CM,FN)
      CALL STS(IOUT,NJ,PAST,M-5,TMX,TMN,'ABS LAT VEL', 'NUMBER',CM,FN)
      CALL STS(IOUT,NJ,DIA,M+5,DMX,DMN,'DIAMETER', 'VOLUME',CM,FN)
      IF (IFOUT(3).EQ.0) STOP
C
C      A DIAM. CONDITIONAL STATISTICAL ANALYSIS IS MADE FOR EACH
C      COMPONENT OF THE EXP. RANDOM DATA VECTOR IF IFOUT(3)=1.
C
      M=NQUART
      DMX=2750
      DELR=DMX/NQUART
      RMN=0.
      RMX=DELR
      LMIN=1
      IOUT(1)=0
      IOUT(2)=0
      IOUT(3)=0
      IOUT(4)=0
      DO 90 L7=1,NQUART
        L8=1
80      IF (DIA(LMIN).LE.RMX.AND.LMIN.LE.NJ) THEN
          DI(L8)=DIA(LMIN)
          V(L8)=VE(LMIN)
          VR(L8)=VER(LMIN)
          ANGL(L8)=ANGL(LMIN)
          PS(L8)=PAST(LMIN)
          L8=L8+1

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      SUBROUTINE STSV(NP,DATY,NCL,RMNCLY,RMXCLY,TY,TB)
      DIMENSION DATY(NP),TY(NCL),TB(NCL)
      DIMENSION DIVX(1),DIVY(1),TAB(122,22)
      COMMON /DIARNG/ RMNCLX,RMXCLX,DATX(1024)
      IF (NCL.GT.20) STOP 'VALUE OF NCL.GT.20 . REDEFINE NCL. '
      DO 10 J1=1,122
        DO 15 J15=1,22
          TAB(J1,J15)=0.0
15      CONTINUE
10     CONTINUE
      NCLX=120
      NCLY=NCL
      RLSCX=(RMXCLX-RMNCLX)/NCLX
      RLSCY=(RMXCLY-RMNCLY)/NCLY
      RLSCXY=RLSCX*RLSCY
      CALL BDCOU2(DATX,DATY,NP,-NCLX,-NCLY,DIVX,DIVY,RMXCLX,
6      RMNCLX,RMXCLY,RMNCLY,122,TAB,IER)
      TOTAL=0.0
      DO 30 J3=2,NCLY+1
        TBJ3=0.0
        DO 20 J2=2,NCLX+1
          TBJ3=TBJ3+TAB(J2,J3)
          TOTAL=TOTAL+TAB(J2,J3)*(J2-1.5)*RLSCX
20      CONTINUE
        TB(J3)=TBJ3
30     CONTINUE
      DO 40 J4=2,NCLX+1
        DO 50 J5=2,NCLY+1
          TAB(J4,J5)=TAB(J4,J5)/TOTAL/RLSCXY*(J4-1.5)*RLSCX
50      CONTINUE
40     CONTINUE
      DO 80 J8=2,NCLY+1
        SUMTY=0.0
        DO 90 J9=2,NCLX+1
          SUMTY=SUMTY+TAB(J9,J8)
90      CONTINUE
        TY(J8-1)=SUMTY*RLSCX
80     CONTINUE
      RETURN
      END

```

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C

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      REAL FUNCTION SPQUAD(NP,X,Y,X1,X2)
      PARAMETER (NRC=30)
      DIMENSION X(NP),Y(NP),C(NRC,3)
      CALL UERSET(0,LEVOLD)
      IF (NP.GT.30) STOP 'NP.GT.30.- CHANGE NRC IN SPQUAD'
      CALL ICSCCU(X,Y,NP,C,NRC,IER)
      IF (IER.NE.0) STOP
      CALL DCSDQU(X,Y,NP,C,NRC,X1,X2,RINT,IER)
      IF (IER.GT.34) STOP
      SPQUAD=RINT
      RETURN
      END

```

Notation

Roman letters

a	parameter of ULLN distribution function, defined by Equation 3.17
A	area; also amplitude of oscillation in Equation 4.31
A_c	gas core cross-sectional area
A_p	projected area of the particle on a plane normal to the pressure gradient
A_y	projected area of the wave finger on a plane normal to the y -direction in Equation 4.8
A_{z_0}	reference cross sectional area at position z_0
B	body force per unit mass
$B(t)$	Basset integral, defined by Equation 4.41
C_C	correction factor for C_D , defined by Equation 4.54-b
C_D	particle drag coefficient
C_{DSt}	Stokes drag coefficient
d	droplet diameter
d_i	diameter of the i^{th} droplet sampled
d_{max}	maximum droplet diameter
d_{max}^*	parameter of ULLN distribution function, defined by Equation 3.17
$\bar{d}_{pq}$	generalized mean diameter, defined by Equation 3.3
$\bar{d}_{10}$	mean linear diameter
$\bar{d}_{20}$	mean surface diameter

$\bar{d}_{30}$	mean volume diameter
$\bar{d}_{32}$	Sauter mean diameter
d^{50}	median diameter
d^{90}	diameter below which 90% of the droplet population is contained
D	column diameter
D_c	diameter of gas core
D_e	equivalent diameter
$\underline{D}_i$	data vector of i^{th} droplet sampled
e_{95}^d	mean diameter 95% confidence limits
$e_{95}^{v_y}$	droplet mean lateral velocity 95% confidence limits
$e_{95}^{v_z}$	droplet mean axial velocity 95% confidence limits
e_{95}^{θ}	droplet mean angle 95% confidence limits
E_{oi}	electric field intensity for incident ray
E_{or}	electric field intensity for reflected ray
E_{ot}	electric field intensity for refracted ray
E_{pq}	fractional error of $\bar{d}_{pq}$ as defined by Equation 3.10
f	characteristic frequency
f_d^N	diameter number probability density function
$(f_d^N)_i$	diameter number probability density function value for the i^{th} class
f_d^V	diameter volume probability density function
f_G	grating frequency
f_{Gy}	grating frequency in the y -direction
f_{Gz}	grating frequency in the z -direction
f_i	interfacial friction factor, defined by Equation 5.52
f_i^x	experimental values for the density function of the random variable x
f_M	measured frequency from photomultiplier PM2 (velocity signal)
f_{My}	measured frequency for lateral velocity
f_{Mz}	measured frequency for axial velocity
f_n	natural frequency of the n^{th} order mode
f_{v_y}	radial velocity number probability density function
f_{v_z}	axial velocity number probability density function
f_{θ}^V	volume probability density function of the directional angle θ
$f_{\theta\zeta}^V$	joint volume probability density function of the directional angles θ and ζ
f_{ζ}^V	volume probability density function of the directional

	angle ζ
F_B	particle body force
F_{BY}	particle buoyancy force
F_d^N	diameter number probability distribution function
$(F_d^N)_i$	diameter number probability distribution function value for the i^{th} class
F_d^V	diameter volume probability distribution function
F_D	particle drag force
$F - D^V$	volumetric fraction of droplets function defined by Equation 5.2
F_{DT}	particle drag force at its terminal velocity
F_{FD}	particle form drag force
F_G	particle gravity force
F_S	particle surface force
F_{SD}	particle skin drag force
F_θ^V	volume probability distribution function of the directional angle θ
F_y	finger wave driving force in the y -direction, defined by Equation 4.8
g	gravity acceleration
g_R	force ratio function, defined by Equation 4.59
I	light intensity
$I(x, z, t)$	light intensity spatial function
I_i	light intensity of the incident ray
I_{PM1}	light intensity at PM1
I_{PM1}^0	light intensity at PM1 if no particle is present
I_{PM1}^*	dimensionless relative light intensity, defined by Equation 2.20
I_r	light intensity of reflected ray
I_R	relative turbulence intensity, defined by Equation 4.44
I_{S_j}	light intensity of a ray originating from source S_j
$I_{S'}$	light intensity of the refracted ray in the first droplet interface crossing
I_t	light intensity of refracted ray
I_0	light intensity in the absence of droplet interference
K_D	droplet mass transfer coefficient
ℓ	largest chord in the particle volume in the direction of Δp
ℓ_y	characteristic finger wave thickness in the y -direction
l	distance from the wall of droplet source S_{z0}
L	column length

$\mathcal{L}$	eulerian macroscale of turbulence
L_D	axial distance for droplet deposition
L_F	length of droplet flight
L_{PT}	distance travelled by droplet while immersed in the viewing region
m	liquid film thickness
m_{max}	maximum liquid film thickness
M_A	acceleration modulus, defined by Equation 4.37
n_i	incidence medium refractive index
n_t	refracting medium refractive index
$n(\xi)$	number fraction of droplets with diameter ξ
N	total number of droplets sampled
N_{CLASS}	total number of classes in the variable domain partition
N_D	mass flux rate of depositing droplets on the liquid film, defined by Equation 5.25
N_E	mass flux rate of entrained droplets from the liquid film
N_j	number of droplets in class j
N_P	number of parameters for each theoretical probability density functions
N_{ri}	dimensionless number, defined by Equation 3.21
p	local pressure
p_0	stagnant pressure
P_M	energy dissipation rate per unit mass
r	radial coordinate
r_c	local radius of curvature
r_M	radial coordinate of measurement point
R_c	radius of gas core
Re	particle Reynolds number, defined by Equation 4.27
Re_c	particle critical Reynolds number
Re_G	gas Reynolds number defined by Equation 5.54
Re_{GS}	gas Reynolds number, defined as $(\rho_g U_{GS} D)/\mu_g$
Re_{LS}	liquid Reynolds number, defined as $(\rho_l U_{LS} D)/\mu_l$
Re_M	Re parameter defined by Equations 4.48
Re_T	particle terminal Reynolds number
Re_v	Re parameter defined by Equations 4.49
s	viewing slit gap size
$s_{d_{10}}$	standard deviation of d_{10}
s_F	fringe spacing

s_{v_y}	standard deviation of v_y
$s_{ v_y }$	standard deviation of $ v_y $
s_{v_z}	standard deviation of v_z
s_θ	standard deviation of θ
s_η	standard deviation of η
S	optical parameter defined by Equation 2.25
S_d	diffraction light source
S_{dn}	diffraction light source at particle n
S_J	source with coordinates (x_J, y_J, γ_J)
S_r	reflection light source
S_{rn}	reflection light source at particle n
S_{z_0}	droplet source at A_{z_0}
S_0	original light source
t	time
t_F	time of droplet flight
t_0	initial time value
T	local traction force
u	continuous fluid phase velocity
u^*	friction velocity of gas phase, defined as $(\tau_i/\rho_g)^{1/2}$
u_{rms}	root mean square gas turbulent velocity
U_G	local average axial velocity of gas phase; also average gas velocity, defined by Equation 5.52
U_{GS}	superficial gas velocity, defined as $4W_G/(\rho_g\pi D^2)$
U_{LS}	superficial liquid velocity defined as $4W_L/(\rho_l\pi D^2)$
U_{LF}	liquid film average velocity, defined by Equation 5.50
U_R	relative gas velocity, defined as $U_G - v$
U_S	gas slip velocity, defined by Equation 4.2
$U_{S_{z_0}}$	volumetric flux rate of droplets at source S_{z_0}
v	droplet velocity
v_G	speed of rotation of grating
v_{Gy}	rotational speed of Ronchi grating oriented in a direction parallel to the axial direction
v_{Gz}	speed of rotation Ronchi grating oriented in a direction normal to the axial direction
v_i	interfacial liquid velocity
v_R	relative gas velocity, defined by Equation 4.25
v_{R_z}	z -component of relative velocity vector

v_{R_T}	relative terminal velocity
v_T	droplet terminal velocity
v_y	droplet lateral or radial velocity
v_{y_i}	axial velocity of i^{th} droplet
v_z	droplet axial velocity
v_{z_i}	radial velocity of i^{th} droplet sampled
v_0	initial droplet velocity
V	volume of particle
V_{Sp}	volume of spherical particle
$\overline{v'^2}$	mean square velocity difference between two points in the gas flow field
We	Weber number, defined by Equation 3.23
We_c	critical Weber number
$W_D(L_D)$	mass flow rate of droplets depositing within a distance L_D
$W_D^{RE}(L_D)$	mass flow rate of depositing droplets within a distance L_D that are entrained after A_{Z_0}
$W_D^T(L_D)$	total mass flow rate of depositing droplets within a distance L_D
W_G	gas mass flow rate
W_L	liquid mass flow rate
W_{LE}	mass flow rate of entrained droplets
W_{LF}	liquid film mass flow rate
$x(t)$	particle trajectory
$X(L_D)$	mass fraction of droplets that deposit within a distance L_D from the cross reference section
z_M	axial coordinate of measurement point
z_p	axial coordinate of droplet position
z_S	axial coordinate of center of viewing slit
z_0	axial coordinate of cross reference section

Greek letters

α	proportionality constant in Equation 4.7
α_c	gas core void fraction
β	phase angle in Equation 4.32
γ	angle coordinate between the ray and the x -coordinate; also, density ratio defined as ρ_p/ρ_f
δ	parameter of ULLN distribution function, defined by Equation 3.20

δ^*	parameter of probability distribution function of droplet angle, defined by Equation 5.20
Δ_A	functional parameter defined by Equation 4.38
Δ_H	functional parameter defined by Equation 4.39
Δp_s	surface stress
Δp_T	pressure difference between any two points in opposite tops of control volume at a distance L_D
ζ	droplet axial directional angle coordinate
η	modified angle variable defined by Equation 5.16; also, dampenning coefficient in Equation 4.34
η^*	parameter of ULLN distribution function, defined by Equation 3.14
θ	droplet axial directional angle coordinate
θ_D	deposition angle
θ_i	angle between an incident ray and the normal at the intersection point
θ_r	angle between a reflecting ray and the normal at the intersection point
θ_t	angle between a reflected ray and the normal at the intersection point
μ_f	fluid viscosity
μ_g	gas phase viscosity
μ_l	liquid phase viscosity
ν_f	fluid kinematic viscosity
ρ_c	continuous phase density
ρ_d	dispersed phase density
ρ_f	fluid density
ρ_g	gas phase density
ρ_l	liquid phase density
ρ_p	particle density
σ	surface tension
τ	external stress acting on the droplet
τ^+	dimensionless particle relaxation time, defined by Equation 5.34
τ_D	Stokes number, defined by Equation 4.35
τ_i	interfacial stress
τ_{PT}	droplet passage time
ϕ	angular cylindrical coordinate
ϕ_M	angular cylindrical coordinate of the measurement point
ω	frequency of oscillation in Equation 4.31

∇p	pressure gradient
∇p_E	entrainment pressure gradient
∇p_G	gravitational pressure gradient
∇p_I	interfacial pressure gradient
∇p_T	total pressure gradient
$\nabla_z p$	z-component of pressure gradient vector

general upperscripts

$\bar{x}$	mean or average value of variable x
x^*	theoretical value variable x
x^*	class value variable x

general subscripts*

$\underline{x}$	denotes variable x as a vector
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