

Faculdade de Engenharia da Universidade do Porto



**Creation of VBA-based programs to process and
analyse data obtained from pilot-scale gasification
trials**

Luís Filipe Gonçalves Catalão Côncio da Fonseca

MASTER'S DISSERTATION

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Supervisor: Armando Oliveira
Professor Associado do Departamento de Engenharia Mecânica
Second supervisor: Jean-Philippe Tagutchou
Project manager at PROVADEMSE & Associate Professor at INSA Lyon

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Abstract

Modern sophisticated economies are racing to develop sustainable methods of producing energy. Gasification is a process which promises to hold an important position in the future due to its capacity of turning various kinds of waste into a usable gaseous fuel.

Gasification processes are complex and hard to control and evaluate. They involve immense amounts of variables that must be carefully measured and analysed. These measurements are often returned in the form of mega-data, requiring considerable processing prior to exploitation. Automation of all these processes is of great interest to researchers and engineers.

This Dissertation details the development of VBA-derived programs aiming to process and analyse the vast amounts of data collected during gasification trials conducted at PROVADEMSE's semi-industrial pilot plant located within the Campus of INSA Lyon.

Resumo

As economias modernas e sofisticadas encontram-se actualmente numa corrida desenfreada para desenvolver métodos sustentáveis de produção de energia. Um dos processos que promete ocupar um lugar de destaque no futuro é a gaseificação. Isto deve-se à sua capacidade de transformar vários tipos de resíduos num combustível gasoso utilizável.

Os processos de gaseificação são complexos, e o seu controlo e avaliação revelam-se difíceis. Envolvem uma imensa quantidade de variáveis, as quais devem ser cuidadosamente medidas e analisadas. Esta vasta quantidade é recorrentemente registada na forma de mega-data, que posteriormente exige considerável tratamento antes da sua utilização. A automatização destes processos de tratamento é de grande interesse para investigadores ou engenheiros.

Esta Dissertação debruçar-se-á sobre o desenvolvimento de programas derivados da linguagem VBA, estes visando tratar e analisar a vasta quantidade de dados recolhidos durante os ensaios de gaseificação conduzidos na instalação piloto semi-industrial da empresa PROVADEMSE.

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« Il est encore plus facile de juger de l'esprit d'un homme par ses questions que par ses réponses. »

Marc-Gaston, duc de Lévis

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Nomenclature

Greek Script

α	Seebeck coefficient
β	Ratio between tube diameters
ε	Factor of expansion
η	Gasification efficiency
κ	Von Karman constant
λ	Air-to-fuel ratio
ρ_{air}	Air density
ρ_{fumes}	Density of fumes exiting the boiler
ρ_{propane}	Propane density
ρ_{syngas}	Syngas density
ρ_{water}	Water density
σ	Maximum Deviation - maximum percentual deviation a number contained in an averaging interval can have from the average value
V_{molar}	Molar volume

Latin Script

%CH ₄	Molar percent of methane in the syngas
%CO	Molar percent of carbon monoxide in the syngas
%H ₂	Molar percent of hydrogen in the syngas
%H ₂ S	Molar percent of hydrogen sulphide in the syngas
%O _{2,Air}	Volume percent of oxygen in air
%O _{2,Fumes}	Volume percent of oxygen in fumes exiting the boiler
%O _{2,FumesChimney}	Volume percent of oxygen in fumes exiting through the chimney
%V	Volume percentual composition
Cp _{Air}	Specific heat of air
Cp _{Fumes}	Specific heat of the fumes

$C_{p_{\text{Syngas}}}$	Specific heat of the syngas
$C_{p_{\text{Water}}}$	Specific heat of water
LHV	Low-heating value
LHV_{ar}	Low-heating value, counting moisture and ash (all received)
LHV_{db}	Low-heating value, dry base
$\dot{m}_{\text{AirExtractor}}$	Mass flowrate of air from syngas extraction fan
$\dot{m}_{\text{CombAir}}$	Mass flowrate of air in boiler combustion
$\dot{m}_{\text{Fumes}}$	Mass flowrate of fumes
$\dot{m}_{\text{Propane}}$	Mass flowrate of propane
$\dot{m}_{\text{Syngas}}$	Mass flowrate of syngas
P_{Fumes}	Fumes' power
P_{LHV}	Power from low-heating value
P_{Syngas}	Syngas power
$P_{\text{Syngas,airech}}$	Power received by the air in the heat exchanger
$P_{\text{Syngas,ech}}$	Power transferred from syngas to the heat exchanger
$P_{\text{Syngas,t}}$	Syngas' theoretical power
P	Period for smoothing (number of values counted in each averaging)
$Q_{\text{AirExtFumes}}$	Air flowrate injected into the fumes during extraction
$Q_{\text{AirExtractor}}$	Air flowrate from syngas extraction fan
Q_{CombAir}	Air flowrate in boiler combustion
$Q_{\text{CombAir,t}}$	Theoretical air flowrate in boiler combustion
Q_{Fumes}	Fumes flowrate
$Q_{\text{Fumes,Chimney}}$	Fumes flowrate exiting through the chimney
$Q_{\text{Fumes,t}}$	Theoretical fumes flowrate
Q_{molC3H8}	Molar propane flowrate
$Q_{\text{molC3H8,Syngas}}$	Molar propane (in syngas) flowrate
Q_{molCH4}	Molar methane flowrate
Q_{molCO}	Molar carbon monoxide flowrate
Q_{molH2}	Molar hydrogen flowrate
Q_{molH2S}	Molar hydrogen sulphide flowrate

$Q_{\text{molO2,AirExtractor}}$	Molar oxygen flowrate in syngas extraction fan
$Q_{\text{molO2,CombAir}}$	Molar oxygen flowrate in boiler combustion
$Q_{\text{molO2,Fumes}}$	Molar oxygen flowrate in fumes
$Q_{\text{molO2,Stoich.}}$	Stoichiometric molar oxygen flowrate
$Q_{\text{molO2,Syngas}}$	Molar oxygen flowrate in syngas
$Q_{\text{O2CombAir,t}}$	Theoretical molar oxygen flowrate in boiler combustion
Q_{Propane}	Propane flowrate
Q_{Water}	Water flowrate
N_s	Smoothing number - number of averaging cycles ran during a smoothing process
t	Time interval used to fill the Raw Data Sheet
T_{Amb}	Ambient temperature
T_{LHV}	Temperature at which LHV was obtained

Acronyms

BASIC	Beginner, All purpose, Symbolic Instruction Code
BFB	Bubbling Fluidised Bed gasifier
C&D	Construction & Demolition Waste
C&I	Commercial & Industrial Waste
CFB	Circulating Fluidised Bed gasifier
DRRT	<i>Délégations Régionales à la Recherche et à la Technologie</i>
DSS	Dried Sewage Sludge
DSTO	Defence Science and Technology Organisation of Australia
EEDEMS	<i>Évaluation Environnementale des Déchets, Effluents, Matériaux, Sédiments et ols pollués</i>
FEDER	<i>Fonds Européen de Développement Régional</i>
GHG	Greenhouse Gases
GVI	Graphical User Interface
GWV	Graded Wood Waste
IDE	Integrated Development Environment
INSA	<i>Institut National de Sciences Appliquées</i>

M&Q	Mining & Quarrying Waste
MSW	Municipal Solid Waste
NCV	Net Calorific Value
NRP	Non-Recycled Plastic waste
POLDEN	<i>Pollution Déchets Environnement</i>
PROVADEMSE	<i>Procédés Propres Valorisation Dépollution Matières premières Secondaires Effluents et Energie</i>
RAD	Rapid Application Development language
RDF	Refuse Derived Fuel
SRF	Solid Recovered Fuel
TDF	Tyre-Derived Fuels
VBA	Visual Basic for Applications

Chapter 1 Scientific Context

Humanity's energy needs have displayed an increasing growth ever since civilisation took root. Nevertheless, this growth has been staggeringly ever-more-pronounced in recent decades; and is not projected to slow down for the foreseeable future. Indeed, the levels of energy consumption are expected to rise by about 19% in the OECD countries and 81% in the rest of the world from 2005 to 2030 - that is, a total growth of about 50% worldwide (Tagutouchou, 2008).

It is no wonder, then, that the scientific community is ever more preoccupied with discovering, or perfecting, means of obtaining cleaner energy - or indeed of putting worn materials (waste) to new uses. The present dissertation will be especially concerned with the use of gasification for such effects.

This initial chapter will give an overview of the present context as pertains to the use of biomass as an energy source, more specifically its conversion into a biofuel, and will then focus on the production of syngas - product of gasification - from waste-derived fuels. All of these concepts are important to understand the work undertaken by the company PROVADEMSE, where the internship leading to this dissertation took place.

PROVADEMSE is a company focused mainly on soil depollution and waste removal or reuse. Of particular interest to this dissertation is its use of a complex gasification plant, with a series of sensors imbued all throughout it. This plant is used to turn biowaste into syngas, later to be burned to produce energy. Chapters 2 and 3 will provide ample information about both gasification and the types of sensors used in the aforementioned plant. From Chapter 4 onwards the work undertaken at PROVADEMSE - the creation of VBA-derived programs to process the data collected from the gasification plant's sensors - will be discussed in detail.

1.1 Biomass as a source of energy

If one were to ask most people today to name a source of renewable energy it is very likely that the most immediate responses would be wind, hydraulic or solar energy sources.

Nevertheless, the source mankind has been exploiting the longest, effectively ever since our ancestors learned to produce fire, is biomass (Guo *et al.*, 2015). Biomass refers to organic material coming from living organisms or, in other words, plant material and animal waste. Energy can be accumulated in these materials due to the process of photosynthesis (Equation 1.1): it stores energy from the sun to convert carbon dioxide and water into glucose and oxygen (carbohydrates, complex compounds composed of oxygen, carbon and hydrogen) (National Geographic Society, 2012).

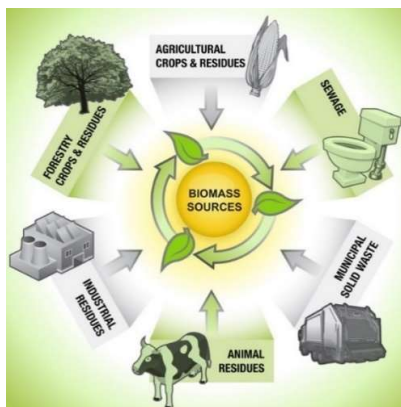
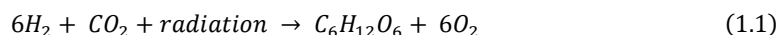
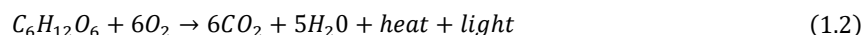


Figure 1.1 - Illustration of the various possible sources of biomass. (Zafar, 2019)

By reversing this process, humans have been able to harvest this energy for our own use. This is a rather fancy way of describing the act of burning wood - the earliest use of bioenergy (Guo *et al.*, 2015). It is broadly described by Equation 1.2:



Precisely how mankind came to master the use of fire remains a mystery. It is assumed that natural phenomena such as lightning strikes or volcanic eruptions are very likely to have played a part (Guo *et al.*, 2015). Regardless, eventually our forebears learned how to ignite combustions on their own - the first great scientific discovery with long lasting effects. Indeed, the original uses of firewood are still with us - preparing food, warmth, land clearing, smelting, clay treatment and even war -though the way we consume firewood has been progressively refined (wood chips or wood pellets) so as to maximise efficiency.

It can easily be argued that great technological and civilisational leaps of human history are closely linked with the invention of new methods for harnessing energy (Zou *et al.*, 2016). To provide a clear example, the Bronze Age is commonly understood as representing an enormous technological leap for humanity (Maly, 2015). Our species learned how to handle metal for the first time - it is hard to overstate just how important this knowledge was to become. Still, the relatively measly temperatures attained by simple firewood combustion (~250°C) were far from sufficient for the melting of metal, which requires temperatures of at least 850°C. Our ancestors found an ingenious solution in the development of pyrolysis: by being submitted to this process, wood becomes charcoal, a carbon-enriched, porous, greyish black-solid, with an energy content of 28-33 MJ/kg, higher than even that of coal (Guo *et al.*, 2015). Charcoal burns without flame and reaches temperatures up to 2700°C. This handy material was used for metallurgical effects, namely the smelting of copper and iron ores, and so kickstarted the

Bronze Age 5000 years ago. Charcoal again became critical from the 1930's to the 1960's, as a scarcity of gasoline in China and Europe (due to the War) led to many automobiles being powered by wood gas - a mixture of carbon monoxide and hydrogen obtained from the burning of charcoal in a gasifier. And today charcoal remains in widespread use for the purposes of cooking, barbecuing, heating, purification of air and water, drawing and steel-forging. This demonstrates how long lasting some of these discoveries can be.

Having affirmed that wood - a biomass - was the leading energy feedstock for humanity for millennia until recently (Guo *et al.* 2015), it has not been established how it was that fossil fuels came to be so utterly dominant. It comes as no surprise that the key event was the Industrial Revolution, a momentous period in human history which brought about unprecedented and tremendously fast changes to what had hitherto been our way of life (Kool, 2020). As it happens, fossil fuels have been used by mankind since at least 4000 B.C., wherein the carving of coal out of black lignite was reported in the Fushun mines of northeast China. A similar story can be told for petroleum (rock oil) and natural gas. Though it would not be until many centuries later that mankind would discover how to extract and refine petroleum, the small amounts of it that seeped out into the surface were being used thousands of years ago - indeed, Herodotus the historian tells us that asphalt was used in the construction of the walls of Babylon (modern-day Iraq). Moreover, the use of asphalt by the Sumerians in Ancient Mesopotamia (4000 B.C. to 2000 B.C.) was integral for the sculpting of their mosaics and columns, a wonder of Ancient art and architecture. The use of oil for the lighting of lamps or warfare by the Classical civilisations is also well-documented. As for natural gas, in 500 B.C. the Chinese were using bamboo shoots to transport natural gas to boil water. Natural gas was often a source of terror for our ancestors, as they could not understand why it was that, suddenly, extremely hot fire was bursting from the ground (natural-gas reserves).

Given their immense energy density, these fuels became very successful. In fact, the principle behind their use as an energy source is similar to that of "regular" biomass - only much more densely packed (Maly, 2015). Coal, a black sedimentary rock composed mostly of carbon and hydrocarbons, is the result of the dense, wide forests and algae from as far as the Carboniferous period being buried and compressed under the overlying mud and vegetation (National Geographic Society, 2012). Here, in an oxygen-deprived environment, the increased temperatures and higher pressures led to the plant life decomposing at a very slow rate whilst retaining most of the carbon it absorbed throughout its life cycle. The sheer colossal amount of time it takes for coal to develop is why it is not considered a renewable energy source.

This brings us to a fact one must bear in mind: the renewability of an energy source depends, ultimately, on its rate of renewal versus its rate of expenditure. This may be of relatively minor importance when we are dealing with wind or solar power - which would be impossible to exhaust - but it is crucial when dealing with biomass (National Geographic Society, 2012). An unwise exploitation of this resource can quickly create problems as large as the ones its use attempts to solve. If plant life is not allowed to rejuvenate at the same rate as it is being exploited, then there will be an increase in the total amount of carbon dioxide as plant life is unable to absorb all of the gas being released. This is, of course, a simplistic explanation of the issue, as the size and type of plant life must also be taken into account.

The areas of buried plant matter, from where peat is extracted, are known as peat bogs. These peat bogs, when exposed to sufficiently high heat and pressure, will suffer extraordinary

compression (its size being reduced by a factor of ten) and become coal (National Geographic Society, 2012). The underground formations where this phenomenon took place are named coal seams, or coal beds. These reserves are especially large in the U.S., Russia, China, Australia and India. The size of the reserves was not especially relevant in ancient times, however - ease of access was a heavier factor (Kool, 2020). The British Isles have been especially blessed in this respect, where lumps of coal (called “seal coal” by the locals) could be found by simply strolling through the beach. This abundance led to great coal exploration by the Romans, and many signs of its use, for metallurgy or the heating of baths, are visible not just in the former Hadrian’s Wall but also in the towns of Chester and Bath, as well as many other former cities of the Empire to where the Romans had taken British coal. Overtime, in Europe, coal came to slowly replace charcoal as the main fuel used in metallurgy. During the Middle-Ages, great surface deposits were being mined not just in the British Isles, but in Central Europe as well. By the late Middle-Ages wealthy households were using coal as a heating fuel. A similar phenomenon was occurring in the Americas, with the amusing detail that the Aztecs also used this material for decorative purposes. As coal burned more efficiently and cleanly than charcoal, it eventually came to replace it almost completely in countries where it was abundant (e.g. the Netherlands in the 17th century). And so it was that the stage was set for coal to become as crucial as it did when, in 1769, James Watt presented his steam engine to the world - and thus started the Industrial Revolution, hurling humanity into an ever-more-dynamic frenzy of invention, accelerating manufacturing production, creating machines and factories in huge scale and bringing about the modern age. In 1780, for the first time ever, coal supplanted wood as the leading source of energy (Zou *et al.*, 2016).

With the invention of the Otto engine by Nikolaus Otto, in 1863, the perfecting of the motorcar by Karl Benz in 1888 and the introduction of the means of mass production by Henry Ford in 1908, petroleum-derived fuels became tremendously dominant. Indeed, they feed the automobile industry, which has dramatically changed the way we transport ourselves, all the while exponentially increasing the demand for petroleum (Kool, 2020). The use of natural gas did not have such an explosion. It is documented as being used in Britain in the late 18th century to power streetlamps and occasionally homes. These sporadic uses notwithstanding, prior to World War II, natural gas was often discovered as a by-product of the search for coal or oil, and miners tended to burn or ignore it, as they had no effective way of transporting it. It became more useful in 1885 thanks to Robert Bunsen and his invention of the Bunsen burner, a device which permitted the controlled mixing of natural gas and air and, from such mixture regulation, control of the intensity of the ignited flame. At this time gas distribution was limited to dwellings close to the source of the gas. It would not be until after the Second World War that advances in pipe rolling and metallurgy, as well as new welding techniques, allowed for the building of sturdy and reliable pipelines.

Concern about the use of these fossil fuels would not be significant until the late 50’s and it took the 1973 oil embargo to really send the major Heats into high alert - it was not just that these fuels were finite and highly damaging to the environment, but also that the concentration of these resources in a few select countries ensured the utter dependence of all advanced economies on them (Ayadi *et al.*, 2016). From here, the search for alternatives to these useful, if nefarious, fuels intensified.

Where biofuels are poised to assume considerable importance in what is purported to be the great energy shift of the coming decades is in the transportation industry (Hassan *et al.*

2013). In the world today there are 600 million passenger cars in circulation, consuming a staggering amount of 3500 million litres of gasoline alone (Guo *et al.* 2015). The over-reliance on petroleum-derived fuels has had disastrous consequences, both for the environment and for human well-being. Despite attempts to create alternative powering technologies, it is likely that engines running on liquid fuel will remain dominant for years to come. Here the importance of biomass can be glimpsed: it is currently the only renewable feedstock material from which liquid fuel can be produced. The two main types of liquid biofuels are bioethanol and biodiesel and it is desirable that they gradually replace, or serve as complements to, gasoline and diesel.

Still the question must be posed: if, in the end, both biofuels and fossil fuels operate under the same principles (releasing stored energy from carbon absorption) then why is it that the use of biofuels is not considered pernicious to the environment? The answer has to do with a concept called “carbon sink”. All plant life (for instance) acts as a carbon sink, that is to say, it extracts carbon from the atmosphere and stores it (National Geographic Society, 2012). Upon its death, it releases it back into the atmosphere - the global balance of this process is actually null. The difference with fossil fuels is that these are gigantic carbon reserves which have laid dormant for a very long time: their release back into the environment severely disrupts the current balance. That is the reason why they are so damaging.

Concerns about climate change, and the renewable energy policies from them, are by themselves sufficient to guarantee that global consumption of bioenergy will see a steady increase in the near future (Zou *et al.* 2016). Of the various developing technologies, the co-firing of lignocellulosic bioethanol and biogas show the highest potential for growth. Should the most optimistic targets and predictions be met, bioenergy may account for 30% of the entirety of the world’s energy demand by 2050 (Guo *et al.*, 2015).

1.2 Types of Biofuels

The methods for energy from biomass are manifold. It may be fired (burned alone to extract energy) or co-fired (used as a complement with other fuels) (National Geographic Society, 2012). The dominant mechanism for energy extraction continues to be thermal conversion where, as its name suggests, heat is the primary agent. Although biomass can often be directly burned, as we tend to do at our domestic fireplaces, more often it undergoes heat treatments to make it more energy dense by dehydrating and stabilising it. Amongst these treatments the most common are torrefaction, pyrolysis and gasification; they are rather similar, the main distinction being the extent to which the intervening chemical reactions occur, a factor controlled by temperature and oxygen levels. It is important to stress, however, that other thermal processes do exist (such as hydrothermal upgrading) but which remain underutilised and are often still in an experimental phase.

Today, biomass is rarely consumed “raw” in sophisticated economies (Guo *et al.*, 2015), generally undergoing some form of treatment prior to its use. Beyond the previously mentioned thermal treatments, we can also have biological treatments - with anaerobic decomposition appearing as a notable example. This refers to a process in which bacteria decompose matter in an anaerobic (oxygen-poor) environment - this decay of the biomass originates methane which can then be burned to produce usable energy. It has growing usage for waste management in landfills (National Geographic Society, 2012). Methane, although a very energy-

dense compound, to the point of being a possible rival to traditional fossil fuels, is notwithstanding a pernicious greenhouse gas and extra care must be had in its handling.

Of all the existent biofuels, liquid biofuels tend to arouse the most interest due to the possibility of acting as a replacement to fossil fuels in the transportation industry. To give an example, this is already somewhat true in the case of Brazil, where nearly 30% of the fuels used in road transportation are biofuels (Hassan *et al.*, 2013). A similar growing trend can be verified in advanced industrialised economies such as the USA and major European countries (Zuo *et al.*, 2016).

There are two main types of biofuel: ethanol and biodiesel. Biofuels in general are commonly classified according to generation - what distinguishes the generations from each other is the raw material used to obtain the biofuel (Guo *et al.*, 2015). These can be first, second, third or fourth generation. First-generation biofuels are acquired through the use of generally edible types of biomass, whereas second-generation biofuels commonly arise from more complex lignocellulosic crops (often planted with this purpose in mind) or municipal waste. If the biofuel comes from algal biomass it is referred to as being a third-generation biofuel. It must be noted that second and third-generation biofuels require the presence of a sturdy and dynamic industrialised economy, which looks for optimised carbon use and is capable of churning out valuable co-products, to say nothing of the fourth generation, requiring high amounts of industrial and technological sophistication .

1.2.1 First Generation

These biofuels are produced from edible biomass, namely starch (potato, wheat, barley and corn) or sugars (sugarcane and sugar beet) (Alalwan *et al.*, 2019). Despite the fact that they reduce the consumption of fossil-fuels as well as CO₂ emissions into the atmosphere through the growth of the crops (which act as carbon sinks and absorb it), concerns eventually arose about their impact on croplands, biodiversity and food supply (Ayadi *et al.*, 2016). They are nonetheless produced commercially at around 50 billion litres per year mostly in the form of biodiesel (bio-esters), bioethanol and biogas. One must bear in mind that the latter, unlike the previous two, is of little to no use in the transportation industry (Guo *et al.*, 2015). These fuels are evaluated according to their usefulness in blending with existing petroleum-based fuels or utility in alternative technologies.

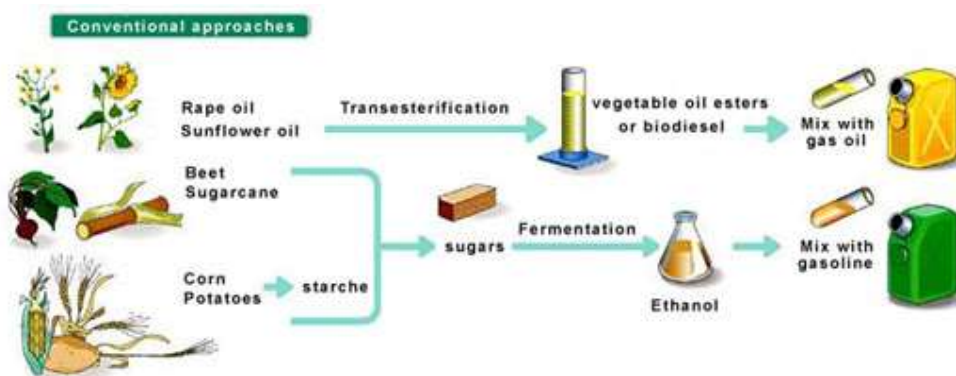


Figure 1.2 - First generation biofuels and their most common feedstocks. (taken from Biofuels: Refueling the future)

1.2.2 Second Generation

Following the food shortages of 2005, concern about the interference of first generation of biofuels with human food sources came to the fore. Efforts were then focused into developing more sustainable production protocols. This heralded the coming of the second generation of biofuels (Alalwan *et al.*, 2019). As many crops of other inedible plant material are planted with the express purpose of producing fuel, the net carbon balance is neutral and even occasionally negative. The feedstock is known as lignocellulosic material due to its composition of lignin, cellulose and hemicellulose - components containing large and complex structures - whose conversion into usable carbohydrates presents a significant challenge (Raud *et al.*, 2019). The technology conceived to exploit these types of biomass is much more versatile in terms of energy conversion (owed to its complexity). This means it can often use by-products from other industries, besides the abundant, inexpensive and readily available nonedible biomass from plant life, waste and abandoned material (Lee *et al.* 2013). Despite its attractive prospects and attention on the part of researchers, this area is, as of now, somewhat underdeveloped and energy production on an industrial scale is still not possible (Siqueira *et al.*, 2020).

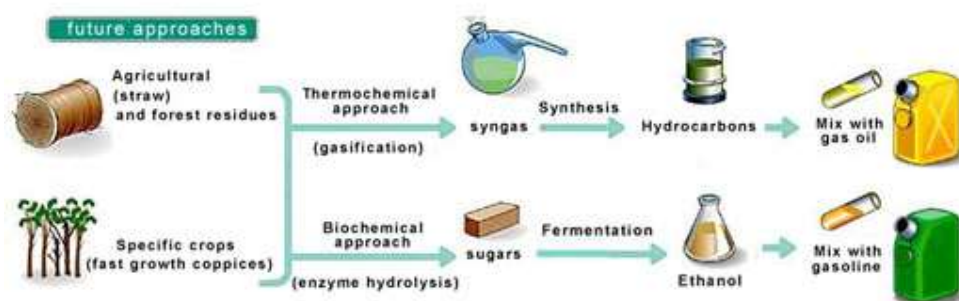


Figure 1.3 - Second generation biofuels and their most common feedstocks. (taken from Biofuels: Refueling the future)

1.2.3 Third generation

The main protagonists of the third generation of biofuels are microalgae. These can be autotrophic, heterotrophic and/or mixotrophic microscopic organisms capable of living in fresh or marine water (Alalwal *et al.*, 2019). It is their photosynthetic ability that confers them their enormous potential to yield special chemicals and nutritional products.

Investigation into biofuel production from microalgae began in California in the 1950's, courtesy of Oswald and Golueke. Microalgae show great potential due to their low-space requirements, high oil content, ability to grow in both artificial and natural environments, eco-friendliness and capacity to produce hydrogen and oxygenic photosynthesis, all the while only requiring light, carbon dioxide and inorganic nutrients. It should not escape one's notice that they are a good carbon sink, consuming 1.8 kg of CO₂ per kg of algal biomass.

Although the oil content of microalgae biomass is subject to significant variety, it is nonetheless considered to be the best oil provider amongst most plants - their oil production capacity per hectare being between 20 to 100 times larger than for palm, coconut, castor and sunflower. From microalgae one can produce not just bioethanol and biodiesel but also methane and hydrogen. An enormous boon of biofuels produced from microalgae is that their properties - density, viscosity, flash point, heating value, cold filter plugging point, solidifying point - are

compatible with international biodiesel standards for vehicles. That is to say, they do not present a need for further treatment upon production. Microalgae are able to attain high lipid content - capacity per dry unit being 15 to 300 times superior to that of conventional biomass - resulting from their high photosynthetic ability. There is yet another advantage to microalgae, namely the elimination of inorganic nutrients from wastewater. Therefore, it is worthwhile to join the two approaches, that of biofuel production from cultivations used simultaneously for wastewater treatment.

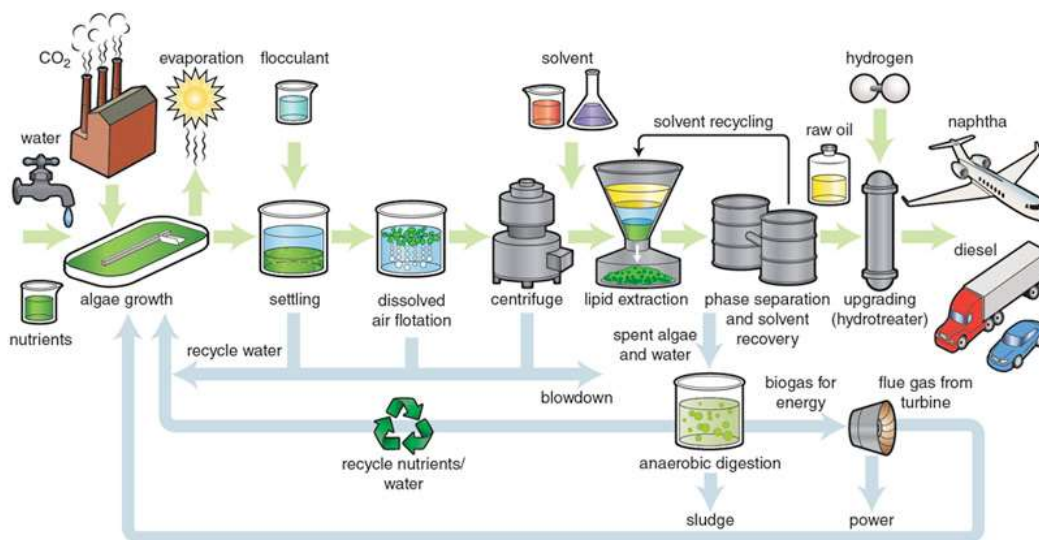


Figure 1.4 - Illustration by Barbara Aulicino of a microalgae biorefinery system. (Pienkos *et al.*, 2011)

Despite the aforementioned advantages, this biomass is very costly, and the biofuel obtained from it is not as stable, owing to the high volatility of algae-produced oil (due to its highly unsaturated nature). This biofuel can be obtained by biochemical or thermochemical processes. The former includes the following: alcoholic fermentation; anaerobic digestion; transesterification and photobiological hydrogen production. The latter, which include anaerobic heating and decomposition of biomass, are preferred as they present better conversion efficiency, smaller production times and respective lower costs.

1.2.4 Fourth generation

Much like the previous generation of biofuels, the fourth generation does not use arable land to extract its feedstocks. Instead, the sources are genetically modified microorganisms such as yeast, fungi, microalgae and cyanobacteria (Abdullah *et al.*, 2019). They can convert carbon dioxide into fuel through photosynthesis. They are seen as a potentially very effective carbon sink (Alalwal *et al.*, 2019). Not much attention will be paid to this generation of biofuels as they are still in their earliest developmental stages. Suffice it to say that the modifications visited upon the feedstock aim to improve the HC yield and create artificial carbon sinks.

1.2.5 Future development and research

It is quite evident that the main focus of biofuel investigations is to reduce their production cost. Additionally, much attention is paid to improve the technology needed to extract biofuel from marine biomass - more precisely, research must focus on: higher efficiency reactors;

continuous operation bioreactor; developing new active and stable catalysts; minimising energy requirements, GHG emissions and waste (Ayadi *et al.*, 2016).

It must be said that the development of these technologies stands very little chance without firm government support. Without said support, the production prices of biodiesel make them a poor alternative to petroleum diesel fuels. Still, research, independent from government action, can still go some way into making biofuels more economically competitive - the most promising alternative today lies with microalgae, and much attention is, and should be, paid to increasing its lipid content and, consequently, is biofuel yields (Alalwal *et al.*, 2019).

It seems exceedingly likely that biofuels will play a very important role in our future energy consumption patterns (Guo *et al.*, 2015). Though it is a fact that first generation biofuels are incapable of competing with fossil fuels due to mankind's food needs, there is no overlap between these two necessities with third and fourth generation biofuels, thus granting them much more long-term potential (Alalwal *et al.*, 2019). As of now, there is great investment in the amelioration of technological sophistication, improving the quality and increasing of biofuel yields from the same feedstocks.

1.3 Syngas

As was mentioned above, fossil fuels are formed in very specific conditions, often under tremendous geothermal heat and pressure and an absence of oxygen (National Geographic Society, 2012). Man has tried to emulate these conditions to treat vegetative biomass and produce fuels of the same ilk, but so far without the intended rate of success. These processes often operate under simulated similar conditions - high temperature, high pressure and little-to-no oxygen (Guo *et al.*, 2015). It is noticeable that these various thermal treatments yield different types of biofuels. For instance, pyrolysis will yield biochar (black, solid residue), bio-oil (brown vapour condensate) and syngas (incondensable vapour). Distinct thermal treatments give rise to various types of biofuels. Whereas gasification will have syngas and slag as its resultant products. All of these can be used for energy production or other industrial and commercial applications.

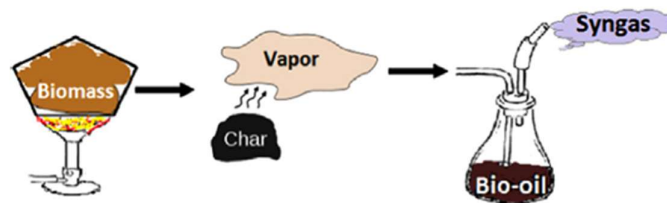


Figure 1.5 - Products obtained from pyrolysis. (Guo *et al.*, 2015)

In this dissertation we are especially interested in one of the products of pyrolysis or gasification: syngas. Syngas consists of 30-60% CO, 25-30% H₂, 5-15% CO₂, 0-5% CH₄ and smaller proportions of water vapour, H₂S, COS, NH₃ and others, these proportions varying according to feedstock characteristics and production conditions (Tagutchou *et al.*, 2013). It is often obtained by gasification, whereby carbon-rich materials - carbon, petroleum, natural gas and dry-plant biomass - are rapidly heated to above 700°C in the combustion chamber of a gasifier and partially burned upon meeting a controlled air flow, resulting in syngas. Wood biomass, following entry into the gasifier, undergoes four phases, namely: drying, pyrolysis, partial

oxidation (combustion) and reduction (Steene *et al.*, 2010). A more detailed explanation of these processes will be given in a later chapter.

Though crude syngas - containing nearly 50% nitrogen as well as minor amounts of tar, particulates, CO_2 and H_2S , with an energy density of approximately 5.3 MJ N/m^3 - can be directly burned to generate electricity it is more usual to purify it and subsequently use it as a source material to synthesise transportation fuel, methanol, ethanol, methane, dimethyl ether and other products (Guo *et al.*, 2015). Purified syngas can, through the Fischer-Tropsch process, be turned into diesel. It can also power hydrogen fuel cells by having hydrogen separated from it - electricity generation and vehicle propulsion have been achieved through this method. In spite of its attractiveness, this purification process is often costly and time-consuming. The conventional methods include physical and chemical adsorption (e.g. water quenching, amine scrubbing). Still, approaches which could be integrated into the gasifier are currently being researched, such as catalytic tar cracking/reforming, CO_2 elimination and H_2 separation.

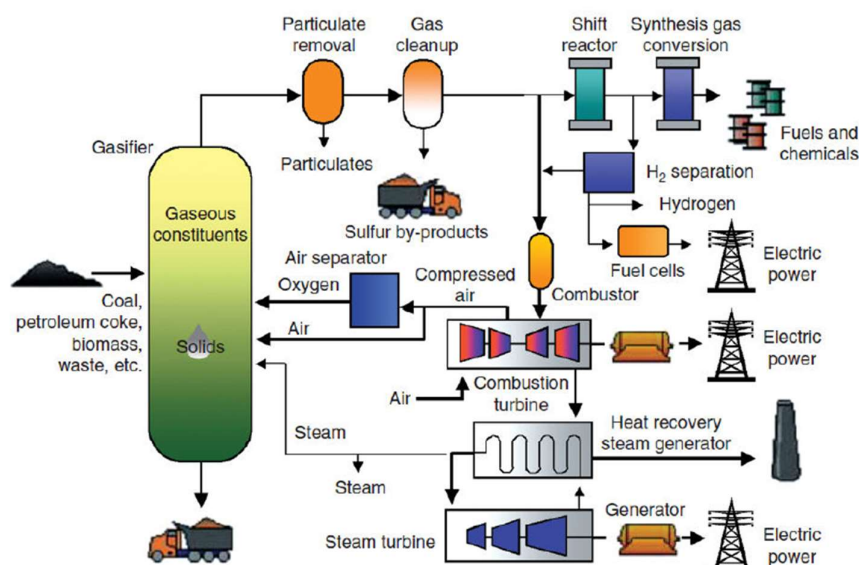


Figure 1.6 - Schematic representation of syngas from gasification/production to use chain. (Liu *et al.*, 2010, cited by Ephraim, 2016)

All-in-all, there are still many obstacles to widespread implementation of gasification - especially the restrictive requirements for feedstock pertaining to moisture and ash content, size, homogeneity, bulk density and energy content - and the process remains at an early demonstration stage (Sansaniwal *et al.*, 2017). More research is needed into making bio-syngas economically viable - despite there being already significant syngas production, only 0.5% of it comes from biomass. 45% of this produced syngas was used to synthesise chemicals, 38% to make transportation fuels, 11% to generate electricity and 6% as gaseous fuel.

Syngas is therefore not seen, for now, as a possible replacement for natural gas (Guo *et al.*, 2015).

The greatest technical obstacles preventing the wider implementation of gasification technologies pertain to the cleaning of syngas (Sansaniwal *et al.*, 2017). The specifications for

this cleaning tend to be quite strict and significant effort is being devoted to finding cheaper ways of cleaning it. Several contaminants can be found in waste-derived syngas, such as:

- Particulate matter;
- Tars;
- Sulphur compounds (HS_2 , COS);
- Nitrogen compounds (NH_3 , HCN);
- Alkali metals (K, Na);
- Hydrogen chloride (HCl);
- Trace heavy metals (Hg, Pb, Cd, Zn);

These can all originate serious issues in gasification systems, such as fouling, clogging, corrosion and catalyst poisoning - causing efficiency and safety concerns. The environmental emissions regulations give the quality requirements for the level of syngas cleaning (Ephraim, 2016).

To clean-up the syngas, three types of technologies, classified according to temperature range, may be used, namely:

- Cold gas clean-up, which often use water sprays, have exit temperatures near ambient conditions ($<100^\circ\text{C}$) to enable water condensation.
- Warm gas clean-up typically occurs at temperatures higher than the boiling point of water up to temperatures of around 300°C which allows for ammonium chloride condensation.
- Hot gas clean-up usually occurs in the temperature range of 400 to 700°C . This results in the condensation of several alkali compounds. Higher temperatures are not usually employed in order to avoid using expensive piping material.

A table is provided below to summarise the various processes and their applications:

Table 1.1 - Overview of different syngas technologies. (Woolcock *et al.*, 2013)

Contaminant	Hot gas clean-up	Warm gas clean-up	Cold gas clean-up
Particulate matter	Cyclones; Barrier filtration; Electrostatic separation; Turbulent flow precipitator (TFP);	Cyclones; Electrostatic separation; Barrier filtration;	Wet scrubbing;
Tars	Thermal cracking; Catalytic cracking; Non-thermal plasma; Physical separation;	OLGA technique (Oil based gas washer);	Wet scrubbing; Biological gas treatment;
Sulphur (H_2S, COS)	Hot adsorption using metal oxides based on Zn, Fe, Cu, Mn, Mo, Co and V, etc.	Semi-wet scrubbing;	Chemical/Physical solvents; Chemical redox; Biological processes; Physical absorption;
Nitrogen (NH_3, HCN)	Catalytic selective oxidation; Thermal catalytic decomposition;	Semi-wet scrubbing;	Wet scrubbing;
Alkali	Hot adsorption using natural minerals	Semi-wet scrubbing;	Wet scrubbing; Condensation;

	(e.g. clays and kaolinite);		
Chlorine	Hot adsorption using Na, Ca and Mg based minerals, etc.	Semi-wet scrubbing using lime slurry;	Wet scrubbing;
Mercury	Hot adsorption using silica, bauxite, kaolinite, zeolite, etc.		

1.4 Use of waste as biofuel

In Europe there are 5 main categories of solid waste (European Commission, 2003):

- Municipal Solid Waste (MSW);
- Commercial and Industrial Waste (C&I);
- Construction and Demolition Waste (C&D);
- Mining and Quarrying Waste (M&Q);
- Agricultural Waste;

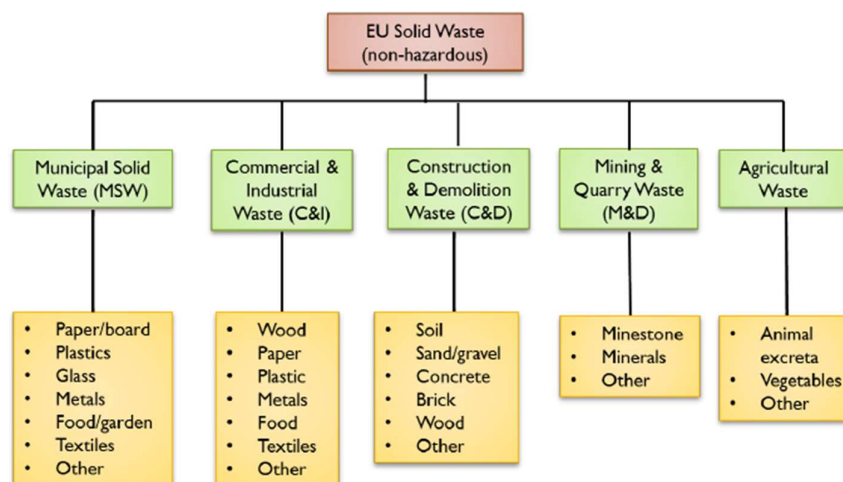


Figure 1.7 - EU classification of non-hazardous waste. (European Commission, cited by Ephraim, 2016)

Fuels can be derived from these kinds of waste. Table 1.1 lists the kinds of waste-fuels available on the market:

Table 1.2 - Types of fuel-derived waste and their origins (Ephraim, 2016)

Type of waste-fuel	Origins
Refuse Derived Fuel (RDF)	Produced from MSW or C&I via processes (shredding, screening, sorting, drying and pelletization) aiming to improve fuel handling or homogeneity.
Solid Recovered Fuel (SRF)	Also produced by mechanical, biological or thermal treatment of input waste. Complies with very tight quality specifications (non-hazardous waste) to be marketed.
Graded Wood Waste (GWW)	Divided into different classes based on the level of chemical contamination. These classifications vary according to country.
Dried Sewage Sludge (DSS)	By-product of urban and wastewater treatment whose water content has been reduced by mechanical de-watering and thermal drying processes. It must have a low water content (<10%) to be used in thermochemical processes.
Non-recycled Plastic Waste (NRP)	Produced from wide variety of sources, with special emphasis on food packaging (MSW). The main plastics to be found in NRP are HDPE, LDPE, PET, PP, PVC and PS.
Tyre Derived Fuel (TDF)	Composed of shredded scrap tyres. These are extremely difficult to recycle given their complex structure and composition and, as such, energy recovery is seen as an attractive treatment for them (Sienkiewicz <i>et al.</i> , 2012).

For the waste type to be eligible for syngas production a series of factors must be in place (Ephraim, 2018):

- Significant and reliable supply of waste for recovery
- Product quality control
- Production of high-quality fuel
 1. Net calorific value (NCV)
 2. Moisture content
 3. Ash content
 4. Cl, N, S, heavy metals
- Policy incentives for the recovery of the waste stream

Should one wish to evaluate the waste-derived fuels, one would be better served by dividing them into two categories: biomass combustibles and petrochemical combustibles.

Table 1.3 - Comparison between biomass and petrochemical waste combustibles. (Ephraim, 2016)

Type	Pros/Cons
Biomass Combustibles	+ Supply is abundant and reliable + EU directives ensure high energy recovery rate - Higher moisture content
Petrochemical Combustibles	+ Superior fuel qualities: high NCV, low moisture content and low ash content - Mixed plastic waste contains high concentrations of chlorine due to presence of PVC. TDF (Tyre-Derived Fuel) often contain Sulphur and Zinc as well - Lower energy recovery rate as most directives encourage their long-term re-use and recycling

What can be concluded is that biomass combustibles are most suited to syngas production. GWW (Graded Wood Waste) have an edge over DSS due to having lower concentrations of ash, N, S and heavy metals (Hg, Cd, Zn and Pb), thus generally producing higher quality syngas. RDF (Refuse Derived Fuel) and SRF (Solid Recovered Fuel) tend to return extreme results, on both ends of the spectrum. Regardless, seeing as SRF is more homogeneous and less contaminated - due to its strict quality specifications - it tends to be more advantageous. If petrochemical combustibles must be used, NRP is the better alternative.

A summary of the criteria used in the selection of waste-derived fuel for the production of syngas is provided in Table 1.4 (Ephraim, 2016).

Table 1.4 - Summary of criteria for waste-derived fuel selection to produce syngas. (Ephraim, 2016)

	Solid Waste Fuel (SWF)		Graded wood waste (GWW)		Dried Sewage Sludge (DSS)	Non-recycled plastic waste (NRP)	Tyre derived fuel (TDF)
	Refuse derived fuel (RDF)	Solid recovered fuel (SRF)	Class A (AW)	Class B (BW)			
Supply							
Quantity (Mt/yr, in 2004)		70.1	70.5	-		26.2	3.2
Energy recovery (Mt/yr, in 2004)		15.1	24	-		4.7	0.8
EU directives		Landfill, IED	Landfill, PPW	Landfill, IED		PPW, IED	Landfill, EVL, IED
Policy incentives		RED, EU ETS	RED, EU ETS	RED, EU ETS		-	-
Product quality control							
Existence of standards	No	Yes	Yes	Yes	No	Yes	No
Fuel quality							
NCV (MJ/kg d) (coal: 20-30 MJ/kg d.)	12-20	11-31	17-20	18.5-23	12-14	30-40	26-32
Moisture content (%) (coal: 3-10%)	15-25	24-32	10-15	10-20	~10-30	0.2	1.2 - 2
Ash content (%), (coal: 5-10%)	10-22	12 -15	1-10	0.4-1.8	30-40	5.3	10-20
Cl (%) (coal: ~0.04%)	0.4-0.6	0.07-0.88	0.01-0.05	0.01-0.03	-	2.4	-
N (%) (coal: 1-2%)	0.6	-	0.1-0.5	0.1-0.8	5	0.6	-
S (%) (coal: ~1%)	0.3	-	0.01-0.1	< 0.05	0.8	0.2	1
Hg (ppm) (coal: ~0.07 ppm)	0.2	0.25-0.45	0.02-0.05	-	0.2-1.8	-	0.17
Cd (ppm) (coal: ~0.01 ppm)	0.8	0.84-1.72	0.05-5	-	2-1500	-	8
Zn (ppm)	-	-	2-100	-	600-20000	-	2000
Pb (ppm) (coal:~3 ppm)	20	44-59.8	0.1-10	-	50-3600	-	410

Directives and Incentives

- Landfill : Landfill Directive, (1999/31/EC)
- IED : Industrial Emissions Directive, (2010/75/EU)
- RED : Renewables Directive (2009/28/EC)
- EU ETS : European Emissions Trading Scheme
- PPW : Packing and Packaging Waste Directive, (1994/62/EC)
- EVL: End-of-life Vehicle Directive, (2000/53/EC)

Colour coding

	Desirable
	Acceptable
	Undesirable

Chapter 2 Theory of Gasification

In the widest possible sense, gasification refers to the conversion of any carbonaceous fuel into a gaseous product having a useable heating value (Higman *et al.*, 2008). This definition excludes pure combustion - which itself exhausts the gas' heating value - but includes pyrolysis, partial oxidation and hydrogenation. Pyrolysis used to be the main gasification process but has, in recent years, lost its spot to partial oxidation¹. In this dissertation we will refer to gasification as a combination of processes, namely pyrolysis, partial oxidation and reduction. What we are interested in is the production of synthesis gas (syngas) - a gaseous product consisting of hydrogen and carbon monoxide. The oxidant may be pure oxygen, air or steam (Tagutchou *et al.*, 2013).

2.1 Historical development

The thermochemical process of gasification developed with the increase in demand for fuels, spurred by the Industrial Revolution. Gasification officially became a commercial process in 1812, handled by the London, Gas and Coke Company. It was initially used to produce town gas - extracted from coal pyrolysis followed by a water-gas process. This gas was mainly used for illumination and cooking. It would eventually be seen as a useful raw material for the chemical industry. Nevertheless, it had inherent limitations - not least of which difficulties in long-distance transportation - and would eventually be mostly abandoned after being dethroned by electricity and, later, natural gas².

Gasification saw a brief surge in popularity during the Great Wars, as fuel depletion worldwide led to the widespread use of vehicles with gasifiers attached.

In recent decades gasification has again been the target of significant interest. This results from a combination of factors, be it a desire to reduce CO₂ emissions, obtain energy independence, an increase in prices of traditional fossil fuels, rapid industrialisation of large countries such as India or China, etc. (Sansaniwal *et al.*, 2017). Indeed, when it comes to the

¹ One should bear in mind that pyrolysis is still present in most modern gasification processes, albeit as an intermediate step.

² However, one should not underestimate the considerable importance its development had: it created the infrastructure which would allow for the much later use of natural gas as well as the designing of appropriate equipment to handle and transport volatile gases.

thermochemical conversion of biomass or waste, gasification is seen as an attractive process (Steene *et al.*, 2011). It is capable of using unconventional sources - with an emphasis given to waste from various sources, be they animal, forest, agricultural, urban, etc. - to produce heat, power and applied chemicals (Ephraim, 2016). It is a complex process and careful attention must be paid to its parameters, that is to say the air to fuel ratio, temperature, pressure, etc.

2.2 Component processes of gasification

Fundamentally, the conversion resulting from gasification is possible due to the presence of carbon, hydrogen and oxygen in the feedstock - enabling the formation of a gas containing a mixture of hydrogen, carbon monoxide, carbon dioxide and methane (syngas) (Guo *et al.*, 2015).

Gasification is generally composed of other subprocesses taking place simultaneously, which will be described now:

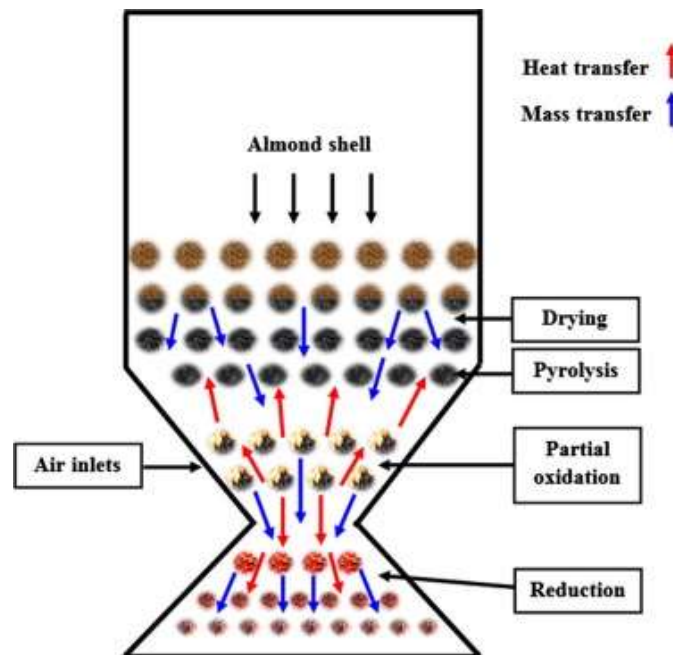


Figure 2.1 - Interior of gasification reactor with all intervening thermochemical processes. (Masmoudi *et al.*, 2017)

2.2.1 Drying

The heat resulting from the other thermochemical processes is used to extract the moisture present in the solid fuel during this phase. Most gasification systems use waste or biomass-derived fuels having a moisture content of 10-20 wt% (Ephraim, 2016). This moisture can be naturally present in the fuel or may have appeared due to stocking conditions (Coulibaly, 2008). It is often trapped in the pores of the solid matrix either as free water (above fibre saturation point), bound water (absorbed within the cell wall fibres - hemicellulose, cellulose and lignin) or water vapour (within the pores). As this fuel enters the gasifier, the heat from the hotter zones downstream will pass onto the fuel, evaporating this moisture - the free water evaporating first, followed by the bound water. This endothermic pre-treatment is very important to optimise the efficiency of the process. It generally happens at temperatures ranging from 200 to 300°C.

2.2.2 Pyrolysis

This is a process of high anaerobic heating. In this phase, the solid fuel is decomposed - the links of the macropolymers (cellulose, hemicellulose and lignite) are broken by the high heat (Sansaniwal *et al.*, 2017). The products of this process will be dependent on the characteristics of the fuel and operating conditions. Though the proportions will vary, the products will be an ensemble of incondensable gases (CO, CO₂, H₂, N₂, CH₄, C_xH_y), of condensable gases derived from steam, organic components, tar and a porous, carbon-based solid called char. Pyrolysis takes place in temperatures ranging from 300 to 700°C (Tagutchou, 2008). It may be either slow or fast. Slow pyrolysis tends to favour the formation of char whilst fast pyrolysis will generally favour the obtention of biooil.

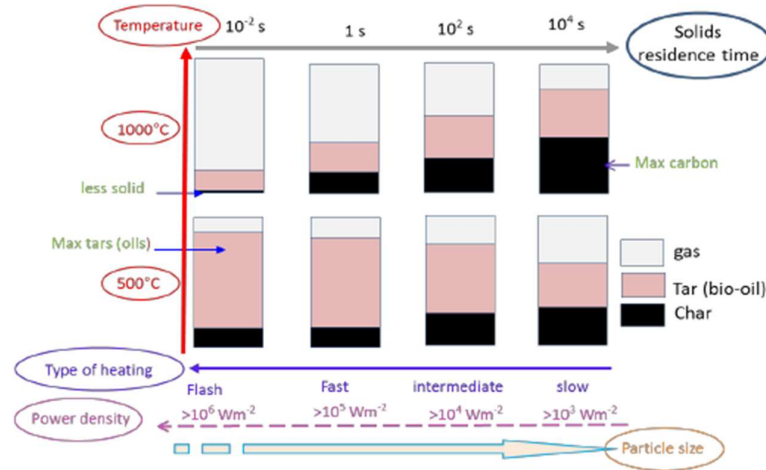
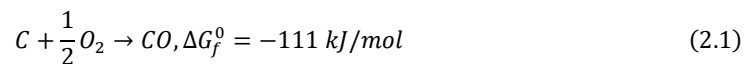


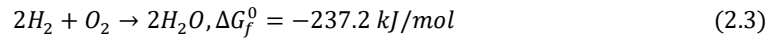
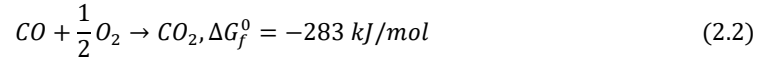
Figure 2.2 - Different pyrolysis yields depending on various factors. (Deglise *et al.*, 2004, cited by Coulibaly, 2008)

Fuels containing high lignocellulosic content tend to increase char yield, whereas high cellulose and hemicellulose content increases gas and tar yields. One might add that alkali salts, when present, tend to catalyse pyrolysis reactions to favour carbon dioxide production over carbon monoxide (Ephraim, 2016).

2.2.3 Partial Oxidation (Combustion)

During pyrolysis there will be a release of a small amount of volatile matter. This matter will come into contact with an oxidant - generally air or steam - resulting in localised combustion (Tagutchou, 2008). This step is very important as it allows for the temperature increase needed for the other (endothermic) steps (drying, pyrolysis and reduction) and for tar decomposition. Indeed, this is a critical step to the quality of the gas - being strongly influenced by temperature, pressure and oxidising agent. This is an exothermic reaction, originating temperature between 1000 to 1500 °C (Sansaniwal *et al.*, 2017). The presence of this exothermic reaction is essential as most of the remaining processes are endothermic - in other words, this combustion provides the necessary energy for the whole gasification process. The reactions present in this phase are (Higman *et al.*, 2008):

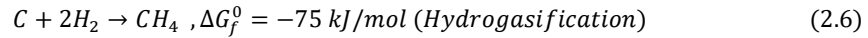
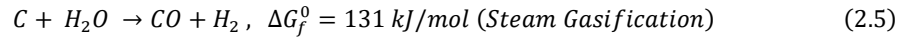
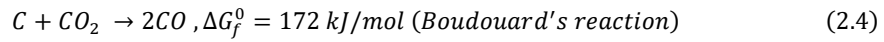




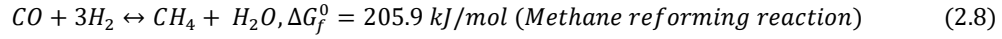
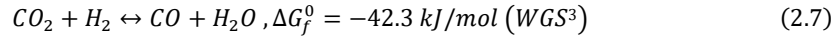
However, it is important that complete combustion does not take place in the reactor. This is controlled by the equivalence ratio, or Air-Fuel ration, in this dissertation symbolised by Φ (Sansaniwal *et al.*, 2017).

2.2.4 Reduction

It is here that the obtained carbon dioxide, steam and char will be partially reduced into carbon monoxide, carbon dioxide, hydrogen and methane - in other words, syngas (Sansaniwal *et al.*, 2017). Here the latent heat is converted into chemical energy, present in the produced gas. The reactions here are (Higman *et al.*, 2008):



These can be simplified and converted into the homogeneous reactions:



Nevertheless, the initial 3 reactions are better representations of the phenomena taking place. The gasification process can be summed up in the following reaction:



All of these reactions coexist in the reactor during the gasification process (Tagutchou, 2008). Their relative effect will vary according to operating conditions, for instance the kind of atmosphere present in the reactor (simple, consisting of pure steam or air, or a mixture of steam and carbon dioxide). The presence and influence of these reactions is the target of significant research (Tagutchou *et al.*, 2013).

2.3 Parameters influencing gasification

2.3.1 Air-Fuel ratio

This parameter compares the experimental air-to-fuel ratio to the stoichiometric one. It is given by Equation 2.11:

$$\phi = \frac{A/F_{real}}{A/F_{stoichiometr}} \quad (2.10)$$

For a given biofuel this ratio is given by Equation 2.12 (Lora *et al.*, 2012):

$$A/F_{real} = 0.0889 \cdot (y_c + 0.375 \cdot y_s) + 0.265 \cdot y_h - 0.0333 \cdot y_o \quad (2.11)$$

³ Water-Gas Shift reaction.

The effect of the air-to-fuel ratio on the syngas composition is displayed in Figures 2.3 and 2.4.

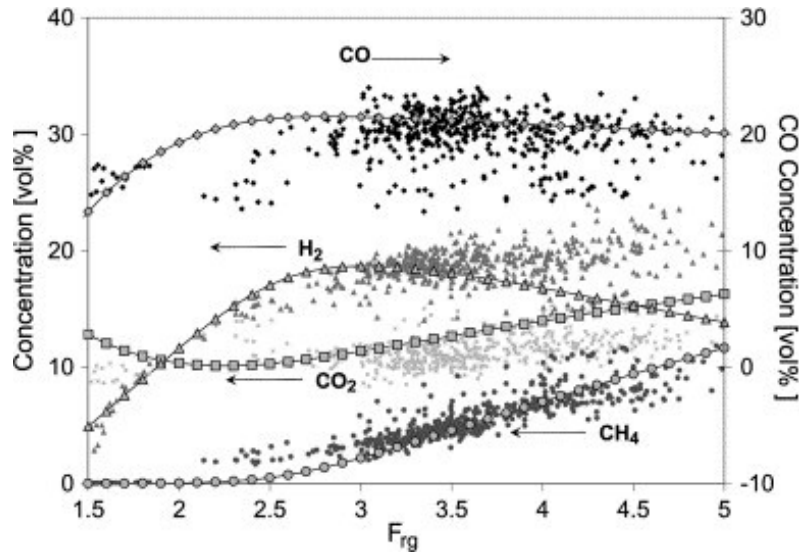


Figure 2.3 - Comparison of the predicted and experimentally obtained producer gas composition for pine wood with 18% moisture. (Melgar *et al.*, 2007)

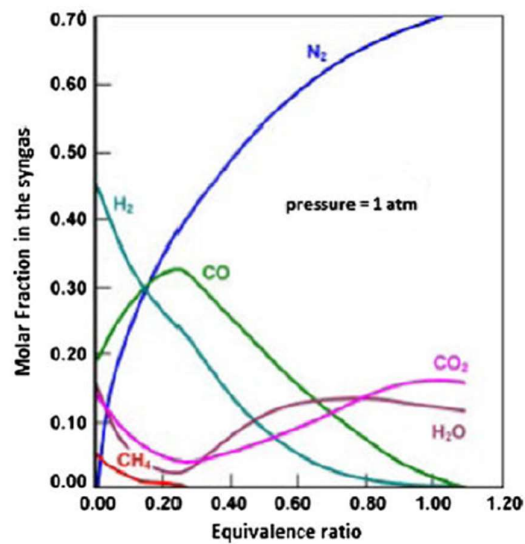


Figure 2.4 - Syngas composition at chemical for different A/F ratios (equivalence ratio), for wood gasification at 1 atm. (Arena, 2012)

2.3.2 Feedstock Moisture content

Moisture is an extremely important element in gasification: it can substantially decrease the efficiency of the whole process, seeing as part of the heat must be used to evaporate said moisture (Sansaniwal *et al.*, 2017). It also affects the composition of the resultant gas. Figure 2.5 relates the volumetric fractions* of the resultant gas and the moisture of the solid fuel.

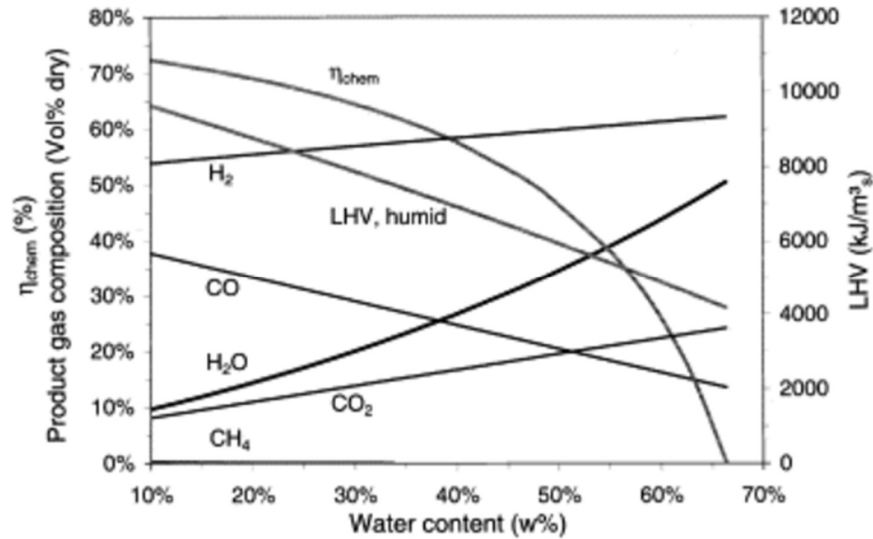


Figure 2.5 - Product gas composition, lower heating value and chemical efficiency versus biomass water content (wet weight basis). (Schuster *et al.*, 2001)

It can be easily adduced that an increase in moisture results in a substantial fall in the production of carbon monoxide along with a more modest one for methane, together with an increase in carbon dioxide and hydrogen.

Figure 2.6 displays the relation between moisture content and the efficiency of the gasification process. One easily ascertains that there is an inverse relation between both parameters - that is, an increase in moisture content leads to a decrease in efficiency.

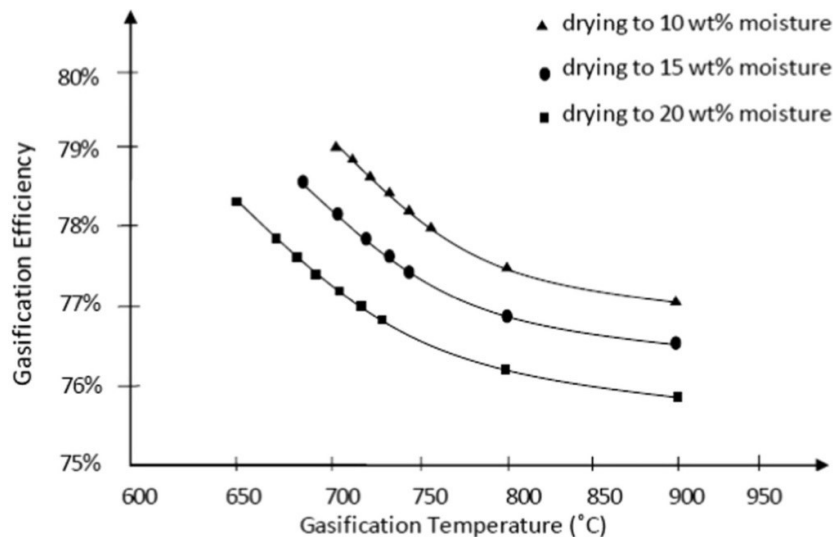


Figure 2.6 - Effect of gasification temperature and biomass moisture on gasification efficiency. (Sansaniwal *et al.*, 2017)

2.3.3 Gasification Temperature

Again, the relative proportion of each of the syngas compounds will be strongly influenced by the temperature at which the process occurs (Lora *et al.*, 2012). An increase in temperature favours the gasification rate (Steene *et al.*, 2011). Higher temperatures also favour the

formation of hydrogen and carbon monoxide, diminishing the amount of methane⁴. Figure 2.7 gives a clearer idea of this:

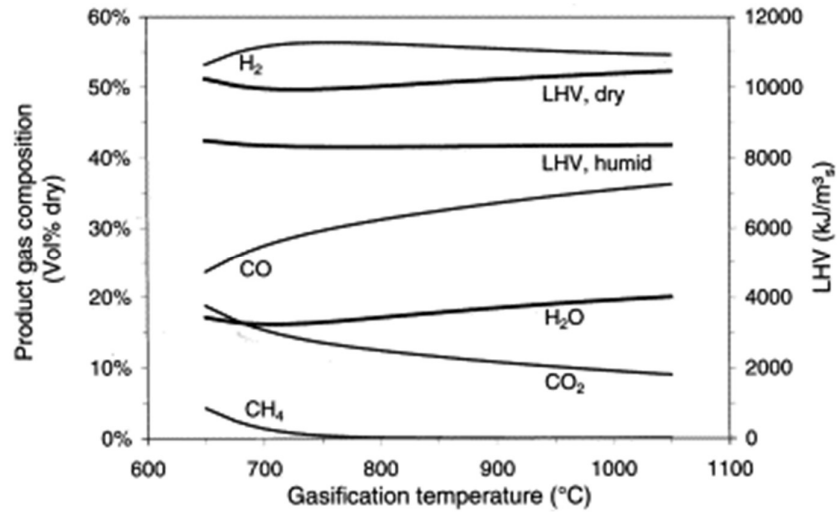


Figure 2.7 - Product gas composition and lower heating value versus gasification temperature. (Schuster *et al.*, 2001)

In Figure 2.8 one might observe a theoretical thermodynamic model (Sharma, 2008) attempting to predict the molar fraction of each component. It is easily observable that a similar trend is present:

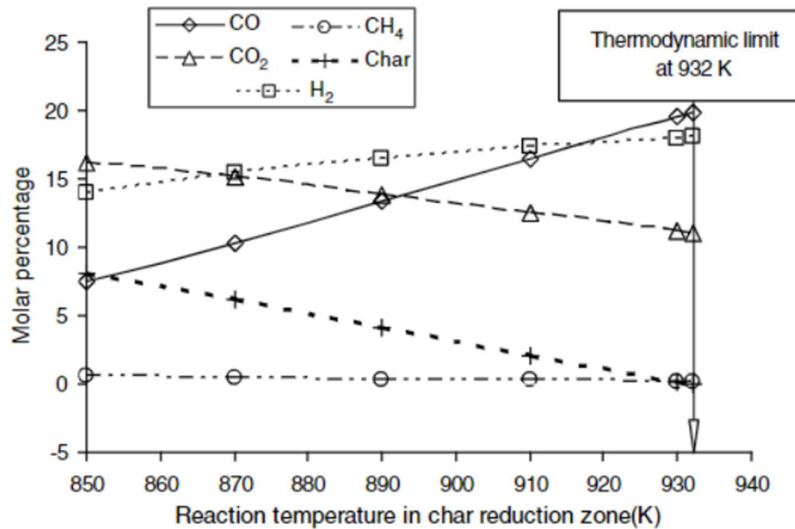


Figure 2.8 - Effect on the syngas composition of the temperature in the reduction zone. (Sharma, 2008)

2.3.4 Residence time

The residence time is closely linked to the attained temperatures. In increase in the residence time allows for a closer approximation to perfect chemical balance - in other words,

⁴ This is in accordance to the principle of Le Chatelier: higher temperatures favour reagents in exothermal reactions, and products in endothermal reactions (Tagutchou, 2008).

a better slag decomposition. It is inversely proportional (to achieve such effects) to the temperature attained (Sansaniwal *et al.* 2017).

2.3.5 Oxidising agent

The composition of the resultant syngas will be largely dependent on the oxidising agent (Sansaniwal *et al.*, 2017). In Table 2.1 one offers an estimate of the relative percentages:

Table 2.1 - Composition of the resulting gas according to the used oxidising agent. (Lora *et al.*, 2012)

Components [z%]	Air	80%O ₂ + Air	Steam
CO	10 - 20	40 - 50	25 - 47
H ₂	9 - 20	9 - 17	35 - 50
CH ₄	1 - 8	<1	14 - 25
CO ₂	10 - 20	19 - 25	9 - 15
N ₂	40 - 55	15 - 30	2 - 3
LHV [MJ/m ³]	4 - 6,5	7 - 9	12 - 17

A comparison of the advantages and disadvantages of using different oxidising agents is provided in Table 2.2.

Table 2.2 - Comparative advantages and disadvantages in the use of different oxidising agents. (Castanheira, 2017)

Agent	Advantages	Disadvantages
Air	- Inexpensive; - Moderate amounts of slag and residual char; - Partial oxidation allowing for the reuse of heat in other processes;	- Low heating value (3-6 [MJ/m³]); - High nitrogen concentrations; - Hard to determine air ratio;
Steam	- High heating value (10-15 [MJ/m³]); - High hydrogen yield;	- Demands an external or indirect source of heat; - High yield of pyrolysis oil; - Needs catalytic; reformation* of slag;
Carbon Dioxide	- High heating value; - High hydrogen and carbon dioxide yield(?);	- Demands an external or indirect source of heat; - Needs catalytic reformation of slag;
Oxygen	- Does not introduce nitrogen into the system; - Absence of slag due to the high attained temperatures; - Gasification of biomass in a liquid state;	- Needs a separate machine to separate it from air;

2.4 Gasification Technology

The type of matter one aims to treat will condition the type of gasification technology to be employed. These can be divided into the following main types: fixed-bed, fluidised bed, rotary kilns, entrained flow, moving grate and plasma reactor (Ephraim, 2016). This is not necessarily exhaustive. A brief description of each will follow.

2.4.1 Fixed Bed

This kind of gasifier is most useful in small plants not requiring great power inputs (<1 MW) (Coulibaly, 2008). They are also called moving-beds since the solid-fuel moves down the reactor. Though they are robust, often small-sized, relatively inexpensive and of simple implementation, they are poorly adapted for greater scales (Sansaniwal *et al.* 2017). Nevertheless, they remain highly popular, and there are many small-scale fixed-bed reactors in use worldwide (Ephraim, 2016).

The direction of the gas flow, compared with the direction of the matter, will serve as a further distinguishing characteristic. These types of gasifier are displayed In Figure 2.9. Their comparative advantages and disadvantages are enumerated in Table 2.3.

Downdraft Gasifier

Also called co-current reactor. Both the fuel and the gasification agent are introduced into the reactor in the same sense, from the top down, with the air (or another oxidising agent) being injected directly into the combustion area from the sides (Sansaniwal *et al.*, 2017). The injection of the oxidising agent in the combustion area will favour the tar cracking above, during pyrolysis, given the high temperatures attained. Therefore, the advantage of this kind of gasifier lies in the low presence of tar in the final product, allowing for the use of the resultant gas to produce electricity. The syngas is extracted below, from the reduction of the char. Nevertheless, the high temperatures present throughout the process have a deleterious effect on the efficiency of the process (Coulibaly, 2008).

Updraft Gasifier

In this case, the matter is again introduced from above, but the oxidising agent is introduced into the bottom level of the gasifier, hence its other denomination as counter-current reactor. The gasification agent pushes the products of the reactions from below to above. This presents the advantage of reusing the heat from the gas to dry the matter, speeding up this phase and permitting the use of more humid feedstock (Sansaniwal *et al.*, 2017). Additionally, the gas is recovered at relatively low temperatures (200-300°C), which is a considerable plus (Coulibaly, 2008). However, this will lead to the production of gases containing a higher slag rate, rendering them unable to be used for electricity production, absent further treatment (Ephraim, 2016).

Crossdraft Gasifier

Crossdraft gasifiers are of a rather simple nature: the fuel enters from the top and suffers the effect of the thermochemical reactions during its descent. Air is injected into the gasifier from the side (Coulibaly, 2008). These gasifiers have the ash bin, fire and reduction zone separated from the machine. This presents limitations when it comes to ash production, as a lessened amount of it can be tolerated (Sansaniwal *et al.* 2017).

They are not without advantages, though: they have fast responses to the fed load; small start-up times; are compatible with dry-air blast and are of a reduced height. Be that as it may, the crossdraft gasifier cannot handle high tar content or very small-sized particles. This, along with the fact that the resultant syngas is extracted at very high temperatures and having had poor reduction of carbon dioxide, explains why, despite certain comparative advantages, the crossdraft gasifier finds very limited use. (Sansaniwal *et al.*, 2017)

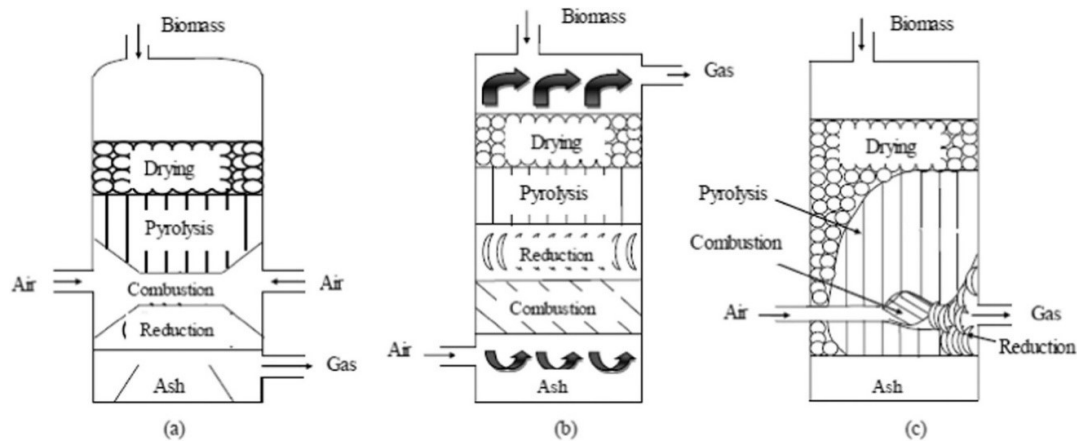


Figure 2.9 - Different types of fixed-bed gasifiers. (a) Downdraft gasifier (b) Updraft gasifier (c) Crossdraft gasifier. (Sansaniwal *et al.*, 2017)

Table 2.3 - Comparative advantages and disadvantages of fixed-bed gasifiers. (Beohar *et al.*, 2012);(Sikarwar *et al.*, 2017)

	Advantages	Disadvantages
Updraft	- Small pressure drop; - Good thermal efficiency; - Little slag formation;	- Great sensitivity to tar and moisture; - Relatively long time required for start-up of IC engine; - Poor reaction with heavy gas load;
Downdraft	- Flexible adaptation of gas production to load; - Low sensitivity to charcoal dust;	- Design tends to be tall; - Not feasible for very small particle size of fuel;
Crossdraft	- Short design height; - Fast response time to load; - Flexible gas production;	- High sensitivity to slag formation; - High pressure drop;

2.4.2 Fluidised Bed

These bed reactors are known for ensuring a highly homogenous mixture and overall temperature uniformity. In a fluidised bed reactor, the thermal treatment of the fuel is done within an enclosed space containing a suspension of fine sands (such as sand, aluminium or dolomite) called bed materials (Sansaniwal *et al.*, 2017). This fluidised state of the fine sands is maintained through contact with the upward flowing gasification medium.

For the good functioning of this process, the waste to be treated must be carefully pre-treated to ensure a sufficiently small granulometry (2 to 5 mm) (Coulibaly, 2008). The gases produced by this process often contain large particles and require further complex treatment before being apt for use - which presents a significant disadvantage of this type of gasifier. These issues notwithstanding, the fluidised bed gasifier generally yields a high-quality fuel, ensured by its excellent gas-solid mixing and the bed's thermal inertia.

They are further distinguished by the speed of the fluidisation.

Bubbling Fluidised Gasifier

In the BFB reactor, the upward flowing gasification agent travels at a speed of around 1-3 m/s and the expansion of the inert bed occurs at the lowermost part of the gasifier. Thanks to its low velocity the bed materials are kept in the reactor and not expelled (Ephraim, 2016).

These BFB reactors can be further classified as low-temperature (<900°C) or high-temperature (>900°C). The former is preferred to prevent ash-fusion and consequent agglomeration, but the latter will yield a better-quality gas by minimising the production of methane or other hydrocarbons. They can operate in both atmospheric and high pressures (10 bar).

Circulating Fluidised Gasifier

In the CFB gasifier the expanded bed occupies the entirety of the reactor. The fluidisation speed is much higher (5-10 m/s). As a consequence of these characteristics, a fraction of the suspension and char is occasionally expelled from the reactor. These pass through a cyclone which reinserts them into the lowermost section of the reactor (Ephraim, 2016).

The gasification process itself occurs in the tall rise. This reactor is particularly suited for fuels with high volatiles - it ensures a long residence time for the gas and fine particles and yields better phase conversions.

In this process the solid phase is in constant circulation within the reactor. This is achieved by separating the solid elements from the gaseous ones through the use of a cyclone, which then reinserts the solid elements into the reactor. Therefore, in this process the fuel benefits from a longer residence time when compared to bubbling fluidised gasifiers, allowing one to obtain better conversions. Here the fluidisation speed is much higher (5 - 10 m/s) and is laxer in regard to granulometry (Coulibaly, 2008).

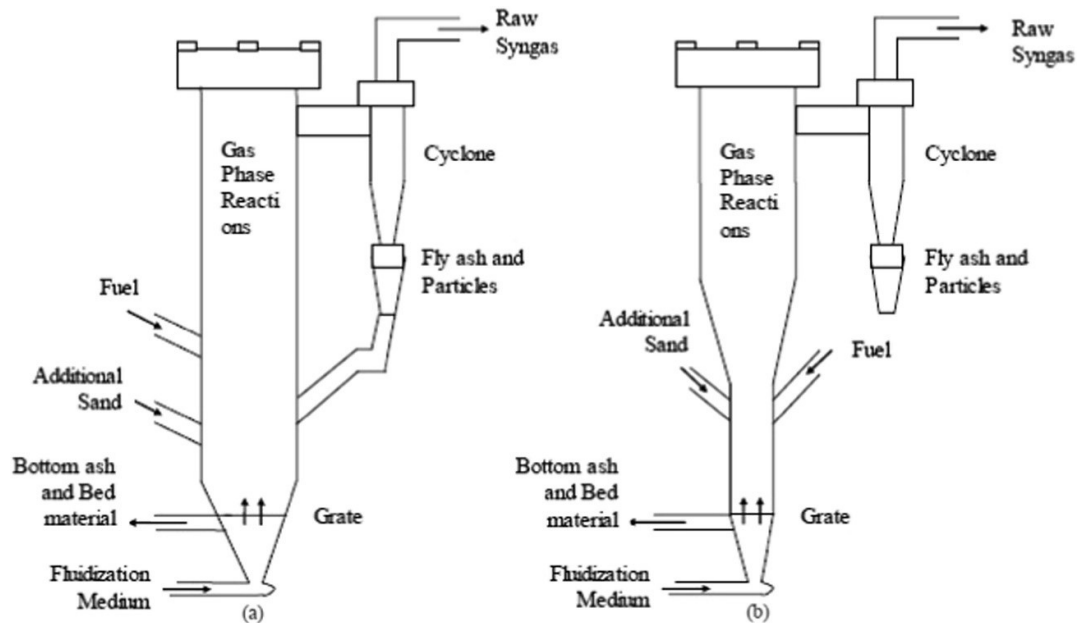


Figure 2.10 - Different types of fluidised bed gasifiers. (a) Bubbling fluidised gasifier (b) Circulating fluidised gasifier. (Sansaniwal *et al.*, 2017)

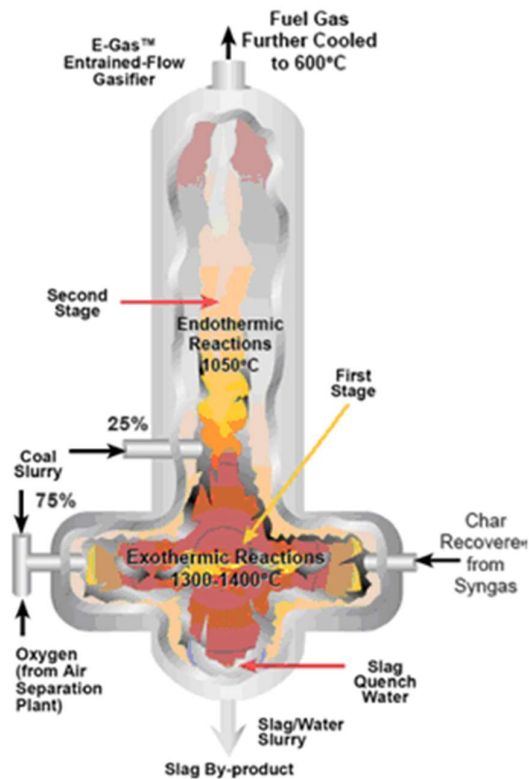
Table 2.4 - Composition of syngas for different gasifiers with air as oxidising agent. (Lora *et al.*, 2012)

Components [z(%)]	Fixed-bed updraft	Fixed-bed downdraft	Fluidised circulating
CO	15-20	10 -22	13 - 15
H ₂	10-14	15 -21	15 - 22
CH ₄	2-3	1 -5	2 - 4
CO ₂	8-10	11 - 13	13 - 15
LHV [MJ/m ³]	3.7 - 5.3	4.0 - 5.6	3.6 - 5.9

2.4.3 Entrained flow gasifier

In this type of gasifier, the fuel must be fed into it either in gaseous form, pulverised or as a slurry, and enters the machine co-current with oxygen or steam. The gasification process takes place at high pressures and temperatures (20 bar and 1200°C, respectively) - the temperature might even reach up to 1500°C (Coulibaly, 2008) -, which ensures the cracking of tar and the production of a high-quality, low tar content syngas. Furthermore, given the high pressures attained in the reactor, this syngas is compressed to the point that it might be directly used in synthesis reactions.

The temperatures reached are so high that some form of cogeneration is advised so as to minimise waste. Also, the short residence times of this reactor can lead to incomplete particle conversion.

**Figure 2.11** - Entrained flow reactor. (Miloni, 2019)

2.4.4 Rotary kiln gasifier

This type of gasifier uses a rotary kiln in a manner reminiscent to the use of kilns in the cement and lime industries. The fuel, along with controlled amounts of air, is fed into the upper end of the rotating kiln. The kiln's movement imposes mixing between the air and fuel and starts the gasification process. The syngas is directed from the high side of the kiln.

These reactors are not at all dependent on particle size or fuel type, which is an unmistakable advantage. They suffer from the difficulties in controlling air flow, as its entrance from the lower end tends to cause full combustions to occur (Ephraim, 2016).

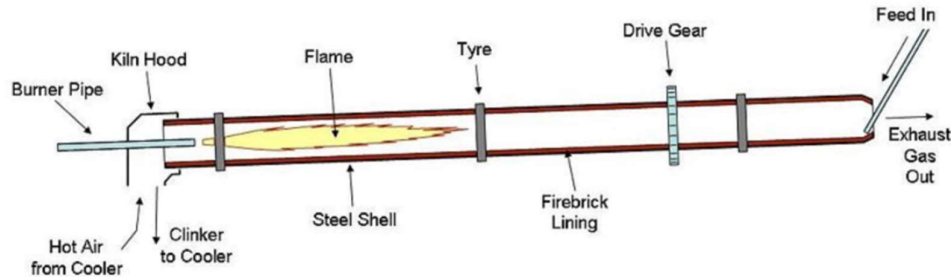


Figure 2.12 - Rotary kiln gasifier. (Fosgitt, 2010)

2.4.5 Moving grate gasifier

This type of gasifier technology operates by feeding the fuel into the gasifier through a moving-grate system, hence the name. It is often used for waste treatment, as the feedstock requires little prior treatment - indeed, this type of gasifier is relatively simple to control and is very versatile both in terms of quantities of fuel characteristics. (Lew, 2020)

The feedstock is oxidised on the moving grate, which must afterwards be cooled by water or air. This moving grate is, in fact, the central piece of the process and must, therefore, be made of special alloys to allow it to withstand high temperatures, erosion and corrosion (Ephraim, 2016).

One potential issued presented by this gasifier is the potential for clogging when it is treating mixed plastic wastes (Ephraim, 2016).

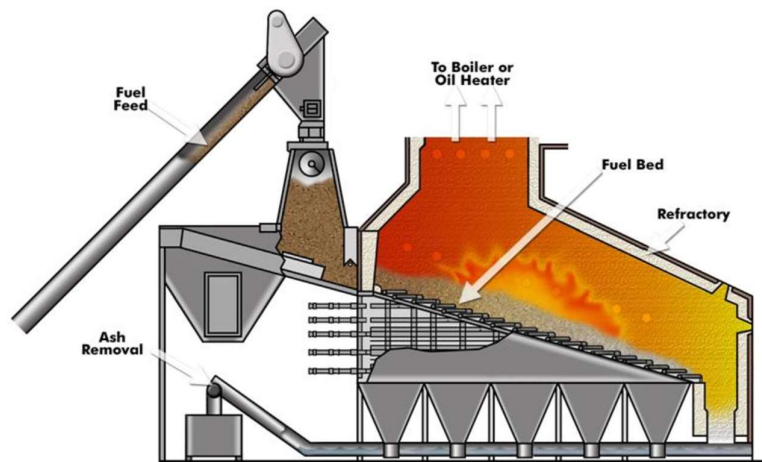


Figure 2.13 - Moving-grate gasifier. (Ephraim, 2016)

2.4.6 Plasma gasifier

Plasma gasification is still in early developmental stage. It uses, generally, DC current plasma torches to generate an electrical arc discharge between two electrodes. These electrodes have plasma gas flowing through them, hence the name. This plasma gas is ionised and creates a very energy dense and hot (2700-4500°C) plasma jet. The plasma torches can either be of the transferred or non-transferred arc type (Valdmunsson *et al.*, 2011).

These reactors have several benefits. The reaction time is very fast, allowing for a compact reactor. No combustion is needed to feed the process, which yields a less voluminous gas stream. Also, it is a process which can be subjected to various forms of control - the plasma torch, being an independent heat source, can be controlled to regulate the process temperature in response to fluctuations from feedstock qualities; similarly, the plasma gas can also be selected to ensure the best reaction environment. Its greatest strength is that, given its extremely high temperatures, it can treat just about any type of waste - indeed, with such temperatures most toxic or hazardous compounds (e.g. dioxin and furans) will be destroyed (Fabry *et al.*, 2013). Needless to say, given the aforementioned characteristics, the quality of the feedstock of little importance to this reactor, seeing as it does not act as its main energy source.

However, it requires an immense amount of electrical power in order to operate. It consumes around 15-20% of its gross power output. Various solutions to this issue are being researched but, for the moment, the economic viability of this technology remains doubtful (Ephraim, 2016).

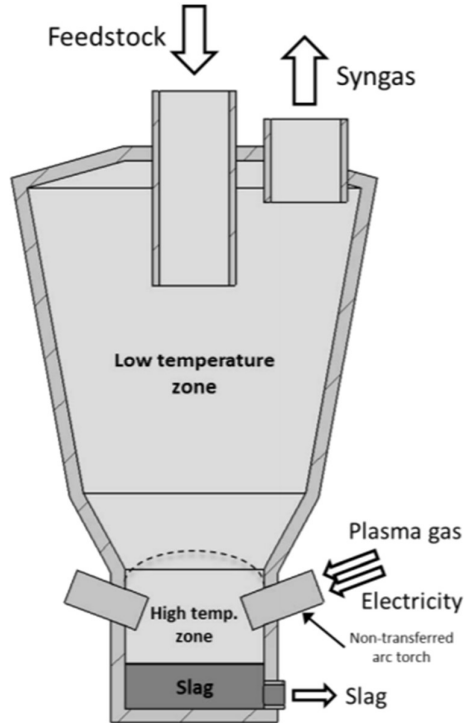


Figure 2.14 - Plasma gasifier. (Valdmunsson *et al.*, 2011)

Table 2.5 provides a summary of the comparative advantages and disadvantages of various types of gasifiers (Sikarwar *et al.*, 2017).

Table 2.5 - Comparative advantages and disadvantages of various kinds of gasifier technology. (Sikarwar *et al.*, 2017)

<i>Gasifier design</i>	<i>Advantages</i>	<i>Disadvantages</i>
<i>Fixed bed/moving bed gasifier</i>	• Simplest and robust design • Economical at small scale • Tolerant for large range of biomasses	• Non uniformity in temperature • High tar and char yields • Poor cold gas η
<i>Fluidised bed gasifier</i>	• Uniformity in temperature distribution • Low tar and char yields • Shorter residence time • High capacity for raw material processing	• Uneconomical for small scale • High PM fraction in syngas
<i>Entrained flow gasifier</i>	• Very low tar yield • Economical for large scale • High quality syngas	• Unsuitable for biomass • Non-tolerant for coarse particles • Issue with raw gas cooling
<i>Plasma gasifier</i>	• Capable to treat hazardous and toxic waste	• High energy requirements • High installation and maintenance costs • Low η

Finally, Table 2.6 compares the specifications of each type of gasifier as pertains to the production of syngas from solid waste (Ephraim, 2016).

Table 2.6 - Comparison between different reactor designs for syngas production from solid waste pyro-gasification. (Ephraim, 2016)

	Downdraft Fixed Bed	Updraft Fixed Bed	Bubbling Fluidized Bed	Circulating Fluidized Bed	Rotary Kiln	Moving Grate	Plasma
Fuel requirements							
Particle size (mm)	< 100	< 100	< 150	< 100	No limit	< 200	No limit
Moisture content (%)	< 20	< 50	< 55	< 55	No limit	< 60	No limit
Ash content (% db)	< 5	< 15	< 25	< 25	< 40	< 20	No limit
Ash melting point (°C)	> 1250	> 1000	> 1000	> 1000	No limit	> 1200	No limit
Bulk density (kg/m ³)	> 500	> 400	> 100	> 100	> 100	250 – 450	> 100
Tolerance of composition variation	Moderate	Low	Very low	Very low	Very high	Very high	Very high
Syngas quality							
Tar content (g/Nm ³)	Low (< 3)	Very high (30-150)	High (~10)	High (~10)	High	-	Very low
Particulate matter	Medium	Low	High	High	High	-	Low
Technology							
Gasification temperature (°C)	700-900	700-900	550 - 1000	900 - 1000	750-1500	-	1,500-5,500
Temperature profile (gradient)	Large	Large	Small	Small	Large	Large	Large
Heat exchange and suspension-to-heat transfer coefficient (W/m ² ·K)	Inefficient (20-100)	Inefficient (20-100)	Very efficient (200-700)	Efficient (100-350)	Very poor (radiation)	Poor (radiation)	- (radiation)
Particle residence time	Particles stay in the bed until their discharge		Long (mins)	Short (seconds)	Very long (1-2 hours)	Very long (> 1 hour)	Long (mins)
Conversion	Very high	High	Intermediate	High	High	Very high (> 90 %)	Very high (can reach 100 %)
Control	Easy	Very easy	Intermediate	Intermediate	Intermediate	-	-
Process flexibility	Very limited	Very limited	Excellent	Excellent	Limited	Limited	Excellent
Scale-up potential	Very limited – low max size	Limited – low max size	Good	Good	Various size kilns available	Very good –long operating experience	Very limited -small scale modules available
Scale	< 5 MWt	< 20 MWt	10< MWt<100	20 < MWt <300	5< MWt <50	-	> 2MWt
Economics							
Cost	Low	Low	Moderate	High	Moderate	High	Very high

Color codes

	Desirable
	Acceptable
	Undesirable

Chapter 3 Sensors in thermochemical processing plants

A vast number of sensors is present at PROVADEMSE's gasification plant. The data collected by these sensors is the backbone of the work undertaken during this internship. This chapter seeks to shed light on the overall functioning of the most crucial of these sensors, namely: thermocouples; pressure sensors; flowrate sensors and oxygen sensors.

An understanding of the principles behind these sensors will be of great aid to understand how the data, later to be processed by a VBA program, is collected - as well as to seek out possible sources of error or routes of amelioration.

Each type of sensor will be treated in its own subchapter.

3.1 Thermocouples

Thermocouples are sensors used to measure temperature. They generate a voltage in accordance to the temperature they detect. They are built using two wire leads made of different metals, welded together into a junction (Zhang *et al.*, 2015). The temperature gradient from the junction along the wire leads will generate two different voltages: it is from this difference that the absolute temperature can be estimated. The principal behind the working of the thermocouple was discovered by Johann Seebeck, to whom it owes its name.

3.1.1 The Seebeck effect

In simple terms, what is known as the Seebeck effect describes the appearance of a potential difference caused by a temperature gradient in two different ends of a certain conductor or semi-conductor material, as well as the proportional relation between the temperature gradient and said potential difference. The temperature difference provokes the movement of charge carriers from the hotter to the colder parts - it is this disequilibrium which leads to the establishment of an internal electrical field and, ergo, the potential difference. The Seebeck coefficient can be understood as the entropy per charge carrier (Molki, 2010).

Prior to Alessandro Volta's⁵ invention of the battery, physicists were rather constrained in their research of electricity. Nevertheless, once knowledge of the capacity to store electrical

⁵ To be fair to Volta, he had, by 1794, discovered that a temperature difference between two ends of an iron rod could provoke spasms on a frog's legs - an early version of the later discovery by Seebeck. Incidentally, Volta was also the first to notice and describe the existence of methane gas.

energy was widespread, this changed dramatically. It would not be long before the relation between electricity and magnetism was demonstrated - notably by Oersted's discovery that electricity flowing in a wire would cause a needle, parallel to it, to budge. This momentous discovery ignited interest all over Europe in the mechanical effects of electrical currents (Hunt, 1964).

Oersted's discovery quickly came to the knowledge of Thomas Johann Seebeck, a Baltic German from Reval, Estonia who worked in the Academy of Sciences of Berlin. In 1821 Seebeck announced that he had ascertained that two different metals, upon forming a closed circle (absent moisture), displayed magnetic properties if subjected to a temperature gradient at the point of contact. He established that the deflection of the magnetic needle arose from the difference in temperature at the metallic junctions; that the effects varied for different metals; and were proportional to the temperature differences. Later on, this phenomenon would be associated to the circulation of an electrical current through the metallic wires.

A lot of work has gone into researching the relation between the type of metal and the Seebeck effect produced. The thermoelectric sensitivity of a specific metal is described by its Seebeck coefficient. For example, iron has a Seebeck coefficient of $19 \mu\text{V}/^\circ\text{C}$ at 0°C , meaning that a positive electromotive force of $19 \mu\text{V}$ will be produced in an iron rod for every 1°C of difference. This relation is only linear for very small temperature changes.

As such, if one is to have a thermocouple made from two distinct metals - metal A and metal B - having therefore different Seebeck coefficients (α_A and α_B , with $\alpha = \alpha_A - \alpha_B$), as well as a temperature gradient between the measuring point (T_2) and the tip of the wire (T_1), one could thus describe the thermoelectric emf (E):

$$E = \alpha(T_1 - T_2) \quad (1.15)$$

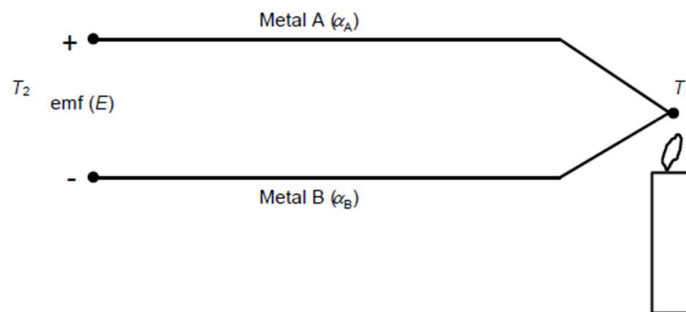


Figure 3.1 - Illustration of two thermocouple wires (α_A and α_B) being heated at the junction and generating a certain EMF. (Molki, 2010)

This effect is today studied for the purposes of energy conversion, but one shall refrain from broaching such subjects as one's interest is limited to the application of the Seebeck effect in thermocouples.

3.1.2 Historical Development of Thermocouples

A. C. Becquerel was the first man to suggest the use of Seebeck's findings in order to measure high temperatures. He communicated to the *Académie Royal des Sciences* in 1826 that, by observing the behaviour of a needle when placed next to wires gradually heated by a spirit lamp, the intensity of the current created by the Seebeck effect was proportional to the

rise in temperature. Furthermore, Becquerel determined that these characteristics were independent of the wire's diameter. Nearly 40 years later, Becquerel's son Edmond would make use of his father's thermocouple, combined with an air thermometer, to determine the melting point of various substances (Hunt, 1964).

The man often credited with popularising the thermocouple is Henry Le Chatelier. He began his curious career as a chemist - studying under Saint-Claire Deville -, being drafted into the army and participating in the 1870 siege of Paris. He would go on to become a mining engineer, eventually becoming Professor of Industrial Chemistry in the French School Mines - and it was within this context that his work on thermocouples took form. He sought a quick and simple method to determine the temperature of cement and decided that thermo-electric couples were the most adequate one. The problem lay with determining the order of magnitude of the error. Chatelet concluded that by discarding the use of metals such as iron, nickel and palladium the thermocouple would become immensely more accurate. He preferred the use of platinum and rhodium. Furthermore, Chatelet advocated the calibration of the thermocouple against the points of fusion or boiling of specific substances, by contrast with the calibration against an air thermometer employed by Edmond Becquerel. Once he arranged for a friend to manufacture this instrument commercially, their reputation spread widely with great speed. As Professor H. M. Howe, famous American metallurgist, put it:

"Thanks to the labours of M. Le Chatelier we have, at last, a pyrometer capable of measuring easily, accurately and rapidly extremely high temperatures, indeed, those approaching the melting points of platinum. And this is not an apparatus which each must construct for himself; it is for sale ready-made. Indeed, it is so far simplified that it has actually entered into practical use for the control of high temperatures in steel works, glass works and gas works."

3.1.3 Thermocouple Characteristics

It should be noted that it is important that the ends of the wires, opposite to the temperature-sensing junction, be at a homogeneous temperature. To ensure this, they are often joined in an isothermal block, often called the Cold-Junction (Duff *et al.*, 2010).

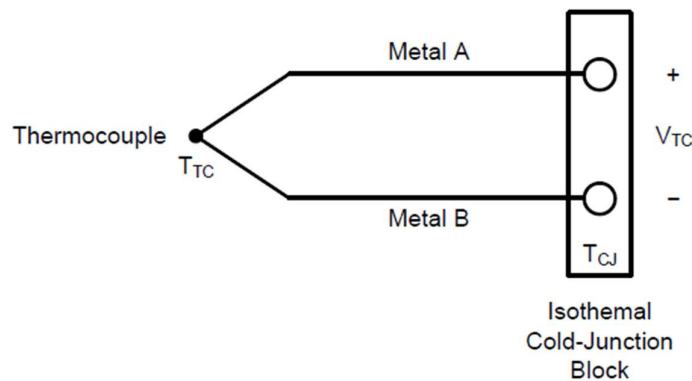


Figure 3.2 - Common thermocouple configuration. (Wu, 2018)

Also, it must be added that any junctions between different metals will create a thermocouple junction. These must be avoided - apart, of course, from that which one does wish to use (Zhang *et al.*, 2015).

3.1.4 Thermocouple types

There are about 13 standardised types of thermocouples (CAPGO®, 2013). For the sake of brevity, only a few will be referred. They are designated by internationally recognised letter-types. This letter does not refer to the metallic composition of the thermocouple, necessarily, but rather to the temperature ranges in which it operates, which may occasion some confusion (Wu, 2018).

Table 3.1 - Characteristics of various types of the thermocouples. Seebeck coefficient at 0°C. (CAPGO®, 2013)

Type	Lead Metal (+)	Lead Metal (-)	Temperature Range [°C]	α [$\mu\text{V}/^\circ\text{C}$]	Comment
J	Iron	Constantan	-210 to 1200	50.37	High temperature; Reducing environment.
K	Chromel	Alumel	-270 to 1370	39.48	General purpose; High temperature; Oxidising environment
T	Copper	Constantan	-200 to 400	38.74	General purpose for low temperatures; Tolerant to moisture;
E	Chromel	Constantan	-270 to 1000	58.70	General purpose. Low and medium temperatures.
S	Platinum and 10% Rhodium	Platinum	-50 to 1768	10.19	Precision; High temperature
N	Nicrosil	Nisil	-270 to 1300	27	Relatively new type, superior replacement for K type.

For very general applications the T-type thermocouple is commonly chosen due to its low-cost, sensitivity and accessibility. In industrial environments K and N-type thermocouples are often preferred, given their suitability to high temperatures. These three types are the only ones present at PROVADEMSE's gasification plant: as such, they will be given a little more attention.

Type T

Its temperature range is limited to -200°C up to +350°C. It is however very useful in food, environmental and refrigeration applications. Tolerance class is superior to other base metal types and close tolerance versions are readily obtainable. The e.m.f/temperature curve is non-linear especially around 0°C and sensitivity is 42 $\mu\text{V}/^\circ\text{C}$.

Type K

Type K remains the most common general-purpose thermocouple. This is readily explained by its low-cost and versatility. There is considerable variability in its characteristics: this is owed to the fact that they were developed at a time when metallurgy had not yet reached its current levels of sophistication. When thermocouples contain a magnetic constituent metal,

they often undergo a deviation in output when said constituent reaches its Curie point - this happens for nickel, present in Type K thermocouples, at about 185°C. Type K thermocouples are well suited for oxidising atmospheres. However, they fare less well in reducing atmospheres particularly in the presence of high concentrations of hydrogen. At high temperatures, it becomes quite difficult to prevent the hydrogen from diffusing through solid metals, making its way into the wires. As it comes into contact with the chromel alloy in the thermocouple's wires, causes the oxidation of the chromium present in it. It will magnetise and develop a mottled silvery skin, often with a greenish colour - hence its name as green rot. The emf output is reduced, affecting the accuracy of the reading. This phenomenon is generally detected by checking for chromel magnetisation.

To prevent this issue, the atmosphere in which the thermocouple operates must be either oxygen-rich or oxygen-free. Other solutions include using an oxygen scavenger - a sacrificial metal sheath which reacts with the oxygen - or, indeed, using another thermocouple. The need for a thermocouple with properties similar to Type K which could also operate in low-oxygen environments led to the development of the Type N thermocouple.

Type N

Type N thermocouples were developed by the Defence Science and Technology Organisation (DSTO) of Australia. Its creator goes by the name of Noel A. Burley. They had the goal of overcoming the principal causes of thermoelectric instability in standard base-metal thermoelement materials (with emphasis on the ones which often plague Type K thermocouples).

A general issue in thermoelement materials is the gradually cumulative errors produced in the returned EMF after long exposures to high temperature ranges. This is due to compositional changes owed to oxidation, carburization or neutron irradiation, and it is very much present as a hysteresis phenomenon for Type K thermocouples. This phenomenon, besides cumulative, is irreversible.

Type K thermocouples also suffer from short-term formation of a crystalline structure by its chromium and nickel elements when exposed to temperatures ranging from 250-650°C. These structures change the general metallic structures and magnetic short-range order of the wires, thus leading to erroneous and unstable readings.

These, and not to mention green rot and certain composition-dependent magnetic transformations, were the reason for the development of the Type-N thermocouples.

Its Nicrosil and Nisil alloy maintains its thermoelectric stability at high temperatures, not suffering from the cumulative drift. They also display no short-term crystal restructure nor green rot in much larger temperature ranges or low-oxygen environments. They can be used in vacuums, inert atmospheres, oxidising atmospheres or dry reducing atmospheres. Attention must be given to their intolerance to the presence of sulphur (Webster, 2017).

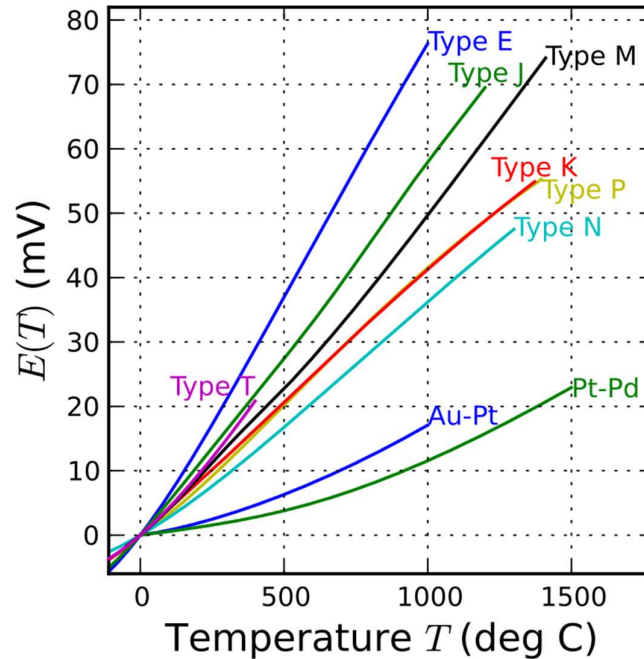


Figure 3.3 - Characteristic functions for various thermocouples types. (Wikipedia, 2014)

Accuracy

Though thermocouples are able to operate over a wide range of temperatures, they are generally only characterised over their stable range. If they are used well below their upper limit, in optimal conditions, they should be able to return very good results. Once they begin to approach the upper limits of their allowed range, a heavier gauge of wire must be used to maintain stability (Wu, 2018).

The accuracy of a thermocouple is affected by its type and temperature. One should remember that the accuracy of the measuring hardware must also be taken into account.

A table is provided below containing the maximum permitted error (in degree Celsius) of each thermocouple type. This table is based on the IEC 584-2 (1982) norm.

Table 3.2 - Maximum error tolerance for each thermocouple in given operating temperatures. (Wu, 2018)

Temperature	B	E	J	K	N	R	S	T
-200	-	-	-	3.0	3.0	-	-	3.0
-100	-	-	-	2.5	2.5	-	-	1.5
0	-	1.7	1.5	1.5	1.5	1.0	1.0	0.5
200	-	1.7	1.5	1.5	1.5	1.0	1.0	0.8
400	-	2.0	1.6	1.6	1.6	1.0	1.0	-
600	1.5	3.0	2.4	2.4	2.4	1.0	1.0	-
800	2.0	4.0	-	3.2	3.2	1.0	1.0	-
1000	2.5	-	-	4.0	4.0	1.0	1.0	-
1200	3.0	-	-	9.0	9.0	1.3	1.3	-
1400	3.5	-	-	-	-	1.9	1.9	-
1600	4.0	-	-	-	-	2.5	2.5	-

These will also depend on the class of tolerable error. This class indicates the permissible temperature intervals at which a thermocouple is used. To give an example, the following graph shows the error of a type K thermocouple (IEC-EN 60584-2) according the temperature range.

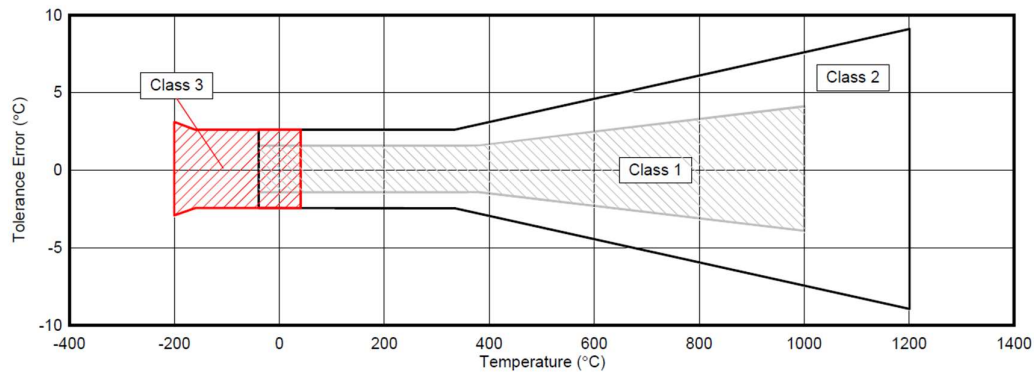


Figure 3.4 - Tolerance of error of a type-K thermocouple with the IEC-EN 60584-2 tolerance classes. It can easily be seen to increase with the temperature range. (Wu, 2018)

Wire Grade

Thermocouple wire can come in different grades. They are mainly divided into measurement wire grade and extension wire grade. The former has higher purity and is meant to be used where greater temperature gradients will be verified. The most commonly used is Class 2, albeit Class 1 - with double the accuracy - are also available (Wu, 2018).

Extension wire grades are meant to connect the thermocouple to the measuring device. This extension may in fact be of a different metal to the measurement grade. They are, nevertheless, chosen to have a matching response over a reduced temperature range. They present lower cost when compared to measurement grade wire, which explains their use.

Wire Gauge

Should the thermocouple's wires be subjected to very high temperatures, they might suffer irreversible changes - such as modified crystal structure; selective migration of alloy components and corrosion on the metal surface. Not to mention the possible changes induced by mechanical stresses. To mitigate these problems the wire's diameter follows a series of stipulated values (CAPGO®, 2013). These are provided in the table below:

Table 3.3 - Guide to wire gauge to use for each thermocouple type in function of temperature. (CAPGO, 2013)

TYPE	8	16	20	24	28	30
J	760	560	480	370	370	320
K	1260	1000	980	870	820	760
T	400	370	260	200	200	150
E	870	620	540	430	400	370
S	1760	-	-	1480	1480	-
N	1260	1000	980	870	820	760

Table 3.4 - Conversion of gauge to millimetres. (CAPGO, 2013)

Gauge	Millimetres
8	4.06
16	1.63
20	0.91
24	0.56
28	0.38
30	0.32

Colour Coding

This parameter requires particular attention, as there are at least 6 different standards worldwide. A table is provided below.

type	Conductor Combinations		Approximate temperature ranges		European DIN	British	American	German	French	Japanese
	+ leg	- leg	Continuous	Short Term	IEC 584-3	BS 1843	ANSI/MC96.1	DIN 43714	NF 42-323	JISC 1610-19E
K	Nickel - Chromium	Nickel - Aluminium (magnetic)	0 to +1100	-180 to +1350						
J	Iron (magnetic)	Copper - Nickel	-185 to +300	-250 to +300						
R	Platinum - 13% Rhodium	Platinum	0 to +1550	-50 to +1700						
S	Platinum - 10% Rhodium	Platinum	0 to +1550	-50 to +1700						
T	Copper	Copper - Nickel	-185 to +300	-250 to +300						
V	Copper	Copper - Nickel	Used for interconnecting Type 'K' thermocouples as an alternative to Type 'K' material. Only used where the interconnection temperature is in the range 0°C to 80°C							
E	Nickel - Chromium	Copper - Nickel	0 to +900	-180 to +900						
N	Nickel - Chromium - Silicon	Nickel - Silicon - Magnesium	0 to +1550	-50 to +1700						
B	Platinum - 30% Rhodium	Platinum	0 to +1550	-50 to +1700						

Figure 3.5 - Thermocouple colour coding for different types and countries. (Thermon®)

Mounting

There are four main configurations for mounting the thermocouples into a sheath - made of stainless steel or Inconel, generally - where it is electrically insulated with mineral oxides.

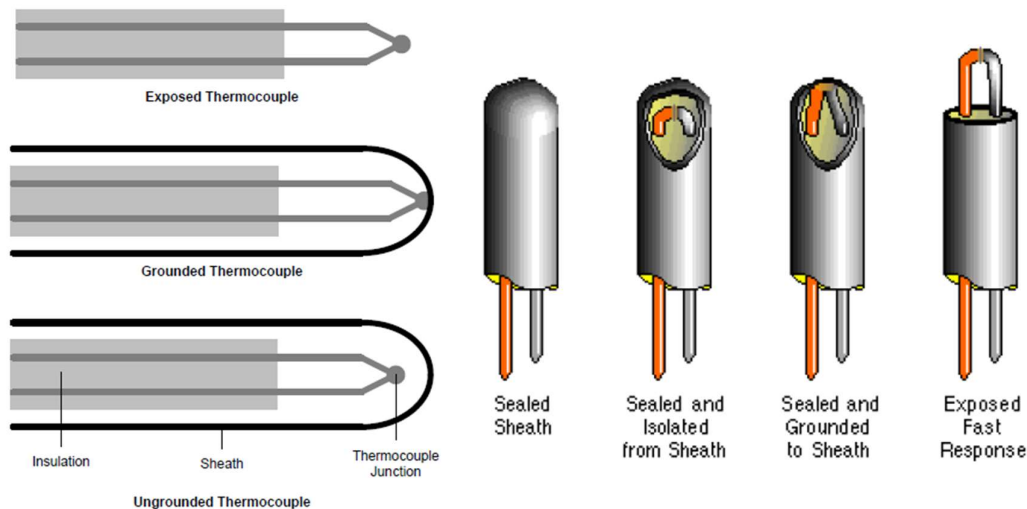


Figure 3.6 - Illustrations of different kinds of thermocouple mounting. (Wu, 2018);(CAPGO®, 2013)

Table 3.5 - Description of various kinds of thermocouple mounting. (Wu, 2018)

Exposed thermocouple	Has no protective sheath. Permits for the use of a small sensor with direct heat transfer from the measured object. Gives a fast sensor response.
Grounded thermocouple	The sensor is welded to the sheath. This latter component is often made of metal, allowing for unburdened heat transfer whilst providing extra protection for harsher environments. However, given the electrical contact between the two components, this type of thermocouple is susceptible to noise from ground loops.
Ungrounded thermocouple	Due to its separation from the sheath, an added layer of insulation is added to the thermocouple. This also means, however, that this configuration presents the slowest response. Also, here too the direct metal contact propitiates the appearance of ground loops.

Pros and Cons

There are good reasons behind the thermocouples' popularity. They are immune to shock and vibration. They can be used over a wide temperature range. They are simple to manufacture, require no excitation power, don't self-heat and can often have very reduced dimensions. They are unchallenged where versatility is concerned (Duff *et al.*, 2010).

Nevertheless, the signal they emit is not only of a relatively low output, it also is non-linear. That means that one requires a sensitive and stable measuring device to provide reference junction compensation and linearization, as well as extra-care to reduce potential sources of noise. The measuring hardware requires good noise rejection capability. Ground loops can be a problem with non-isolated systems, unless the common mode range and rejection is adequate.

3.2 Pressure Sensors

A pressure sensor converts pressure gradients detected in a fluid into a readable value or an electrical signal. An electronic pressure sensing device generates an analogue output proportional to the pressure (Panasonic®).

Depending on the corrosiveness of the fluid, these devices can have a different functioning. For a non-corrosive gas, the pressure will be directly converted into an electrical signal by a transducer, subsequently processed by an amplifier and sent out by an output circuit. However, for other fluids, the pressure will be applied to a stainless diaphragm, and it is the distortion incurred by this equipment which is transmitted to the transducer. From there the functioning is similar.

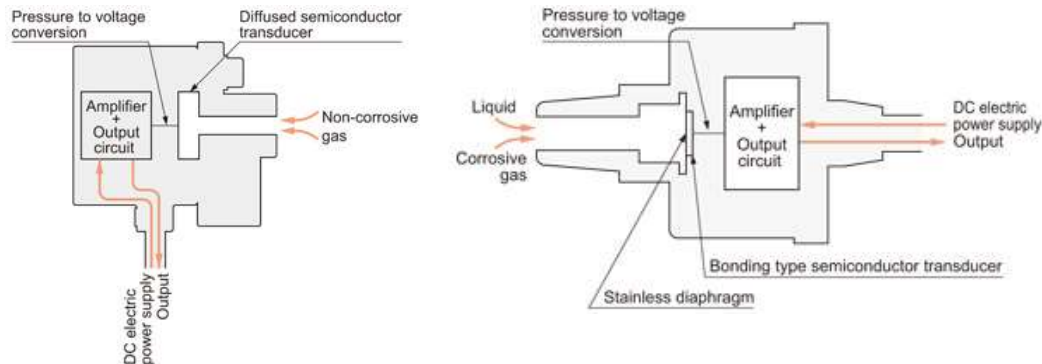


Figure 3.7 - Different configurations of electronic pressure sensors in accordance to corrosiveness of measured fluid. (Panasonic®)

Broadly speaking, there are two types of pressure sensors: electronic and mechanical. The latter one has the great advantage of being inexpensive and, as such, was widely used. Nevertheless, their short life-span and limited reliability led to their gradual replacement by electronic sensors. A table is provided below with examples.

Table 3.6 - Comparison between electronic and mechanical pressure sensors. (Panasonic®)

Type	Electronic (Diffusion, bonding)	Mechanical (Bourdon-tube, manometer)
		
Principle	Direct conversion of pressure into an electrical signal, providing a non-contact reading.	The pressure is directly translated into a mechanical displacement - providing a direct contact reading.
Advantages	High accuracy; High reliability and long lifespan due to the absence of mechanical wearing; Quick response.	Inexpensive; No power supply needed.
Disadvantages	More expensive than mechanical type.	Short lifetime; Poor response.

3.2.1 Methods of classification

Pressure sensors may be classified by three different parameters: applicable fluid, type of pressure and pressure port (Panasonic®). Tables 3.7 to 3.9 below summarise the various types of sensor available.

Classification by measured fluid

The fluid whose pressure is measured could be a gas, water, oil, etc. The transducer which can be used depends on the fluid. Care must be taken as the transducer may be destroyed by corrosion when used with fluids other than those specified.

Table 3.7 - Composition of pressure sensors depending on measured fluid. (Panasonic®)

Type	Description
For noncorrosive gases	Diffused semiconductor is used as the transducer. It can be used to measure air pressure.
For other gases and liquids	Stainless diaphragm is used as the transducer. Besides air pressure, it can be used to measure pressure of gases or liquids which do not corrode a stainless-steel port.

Classification by type of pressure

Classification is based on the reference with respect to which the pressure is measured.

Table 3.8 - Characteristics of different types of pressure sensors depending on pressure-type. (Panasonic)

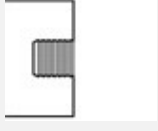
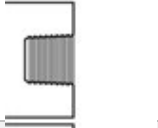
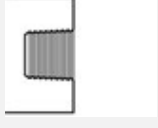
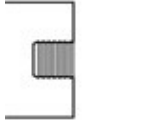
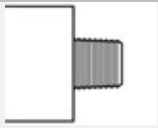
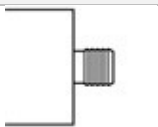
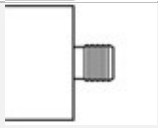
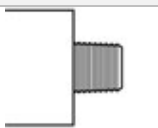
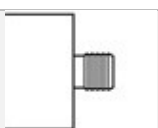
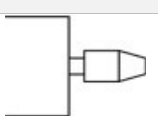
Type	Description
Gauge pressure	Pressure is displayed by taking the atmospheric pressure as zero reference.
Differential pressure	Pressure is measured with respect to an arbitrary reference pressure.

Classification by pressure port

The required pressure port differs with the piping done. If the required shape or size of the pressure port differs, it is necessary to use attachments.

Table 3.9 - Most common types of pressure ports, along with general illustration and characteristics. (Panasonic)

Type	Appearance	Characteristics
Rc 1/8 female thread		• Tapered female thread • Extremely air-tight for high pressure applications • Commonly used in Japan
M5 female thread		• Straight female thread • Fairly air-tight for low pressure applications • Used for low pressure applications

10-32 UNF female thread		• Straight female thread • Fairly air-tight for low pressure applications • Used for low pressure applications • Commonly used in North America
NPT 1/8 female thread		• Tapered female thread • Extremely air-tight for high pressure applications • Commonly used in North America
NPTF 1/8 female thread		• Tapered female thread • Extremely air-tight for high pressure applications • No sealing tape required • Commonly used in North America
G 1/8 female thread		• Straight female thread • Fairly air-tight for low pressure applications, and easily connectable • Commonly used in Europe
R 1/8 male thread R 1/4 male thread		• Tapered male thread • Extremely air-tight for high pressure applications • Commonly used in Japan
M5 male thread		• Straight male thread • Fairly air-tight for low pressure applications, and easily connectable
10-32 UNF male thread		• Straight male thread • Fairly air-tight for low pressure applications, and easily connectable • Commonly used in North America
NPT 1/4 male thread NPT 1/8 male thread		• Tapered male thread • Extremely air-tight for high pressure applications • Commonly used in North America
G 1/8 male thread		• Straight male thread • Fairly air-tight for low pressure applications, and easily connectable • Commonly used in Europe
ø4.8mm pipe		• Easy connection with a tube • Used for low pressure applications

Error inducing factors

There are some sensor characteristics which may influence sensor accuracy, namely (Avnet®):

- Temperature gradients
- Temperature-caused hysteresis
- Pressure-causes hysteresis

- Zero-point error: the start of the measuring range (zero offset) is set too high or too low, shifting the entire scale.
- Span error: The differences between the individual divisions from the zero point to the full-scale value are incorrect and errors are magnified at the upper end of the scale.
- Non-linearity: Distances between the individual divisions from the zero-point to the full-scale value are uneven, turning what should be a straight correspondence line into a curve.

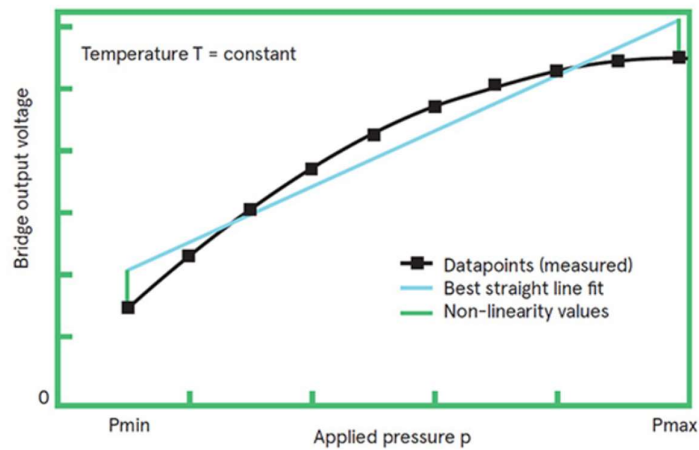


Figure 3.8 - Graphical representation of the phenomenon of non-linearity (Avnet®).

3.3 Flowrate Sensors

In our gasification plant we have two types of flowrate sensors, and both operate according to some variance of the Bernoulli principle (Lipták, 2002).

This principle, deduced by Daniel Bernoulli - after whom it is named - in his book 1738 *Hydrodynamica*, states that when the increase of a fluid's speed there will be a subsequent decrease in static pressure. It is commonly presented in the Bernoulli equation⁶. This is a corollary of the principle of conservation of energy: the flow being steady, there must be no loss of energy along a streamline of the fluid, which would mean that the mechanical and internal energy of the fluid is constant. Therefore, an increase in speed - kinetic energy - necessarily entails a drop both in potential energy (static pressure) and internal energy (Munson *et al.*, 2012).

For the purposes of this paper, one needs only to be concerned with the incompressible form of the Bernoulli equation, as the gases circulating in the gasification plant have a low Mach number - meaning one can assume their density to be constant and the fluid, therefore, incompressible⁷. The Bernoulli equation is thus valid along a streamline:

$$p + \frac{1}{2}\rho V^2 + \rho gh = \text{constant} \quad (3.1)$$

Symbol	Parameter
p	Static pressure at cross section
ρ	Fluid density
V	Mean velocity at cross section
h	Elevation head of streamline at cross section
g	Acceleration caused by gravity

The Mach number, previously briefly mentioned, is a dimensionless number relating the speed of a certain fluid to the speed of sound (Munson *et al.*, 2012). It is given by:

$$M = \frac{V}{c} \quad (3.2)$$

With *c* being the speed of sound in the medium.

Though the first commercial production of a measuring device guided by these principles (also called head metering) happened in 1887 by Clemens Herschel and his Venturi tube, there is evidence that the Ancient Egyptians and the Romans were already aware that the use of orifices had an effect on the speed and pressure of the flow (Lipták, 2002).

⁶ Itself deduced by Leonhard Euler in 1752.

⁷ These devices - as they are directly reliant on Bernoulli's principle - may only be applied to the flow of gases in the absence of their compression or expansion as such phenomena would result in a transfer of energy not encompassed by Bernoulli's equation (in its incompressible flow form). Nonetheless, in an isobaric or isochoric process the energy balance will not be disturbed. One might also ignore the changes in density along the streamline - caused by temperature of pressure variations - if the Mach number is sufficiently low. Alternatively, in many differential-pressure measurement devices, an expansion factor is also used to correct for the density variation upstream and downstream the restriction.

For the sake of completeness, it is important to refer the β parameter - it describes the relation between the restriction diameter and the pipe diameter. Therefore, the relation between the fluid velocity in the pipe and the restriction is given by β^2 .

Another vital number which must be alluded to is the Reynold's number Re_D , proposed by the English scientist Sir Osborne Reynolds in 1883 to explain the zero-velocity profile of fluids adjacent to the pipe walls. This dimensionless number relates the ratio of inertial and viscous forces acting on the fluid (Munson *et al.*, 2012). This number is now vital in describing the behaviour of a fluid. It also exerts a direct effect on the discharge coefficient C .

3.3.1 Pitot Tube

This simple but ingenious invention is the work of Henri Pitot, the French physicist who, in 1732, was the first man to propose a machine meant to measure the speed of water currents. This first version of the machine was based on Galileo's research pertaining to falling bodies, who established the relationship between a body's initial vertical speed and the height it would achieve. This was given by:

$$h = \frac{V^2}{2g} \quad (3.3)$$

All Pitot did, then, was put a tube facing the stream directly and regard the height the fluid achieved when it stopped. From the previous relation he then deduced the flow speed.

From the Bernoulli equation we extract the following deductions:

$$p_t = p_s + \frac{\rho V^2}{2} \quad (3.4)$$

$$V = \sqrt{\frac{2(p_t - p_s)}{\rho}} \quad (3.5)$$

Symbol	Parameter
p_t	Stagnation pressure
p_s	Static pressure
$\rho V^2/2$	Dynamic pressure

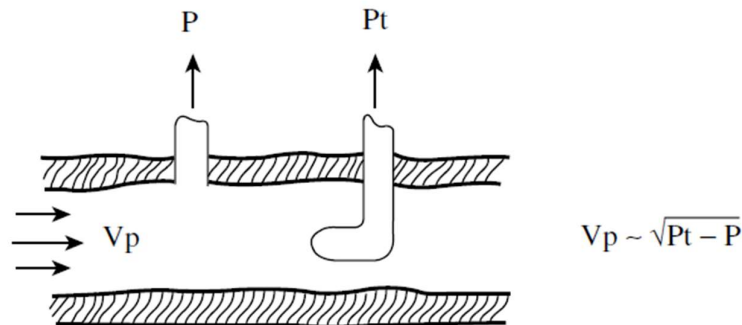


Figure 3.9 - Illustration of the Pitot tube's functioning. (Lipták, 2002)

In other words, operating under our conditions (Reynolds and Mach) we might, from obtaining the static and stagnation pressures, ascertain what the flow speed is. With knowledge of the tube section we then deduce the flow rate.

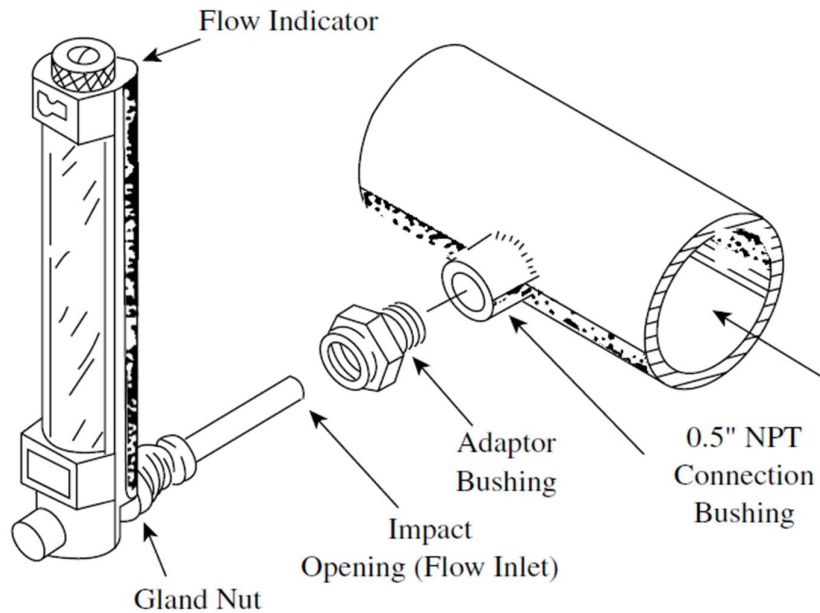


Figure 3.10 - Pitot rotameter with bypass flow entering through impact opening (facing flow) and leaving through static port on opposite side. (Lipták, 2002)

3.3.2 Orifice Plates

Pressure-differential devices are quite common in Europe. They are standardised by the international norm ISO 5167 (Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full). They are divided into nozzles, Venturi nozzles, Venturi tubes and orifice plates - these last devices being the ones one is interested in. They are themselves described in ISO 5167 - 1:2003 (Orifice plates).

Below a table pertaining to the typical accuracy of pressure-differential devices is given:

Table 3.10 - Typical operating for most pressure-differential devices. (Kiš *et al.*, 2013)

Typical accuracy	Max. Pressure (MPa)	Max Temperature (°C)
0.6-2% from range	50	1000

According to the norm, what is actually directly calculated upon the introduction of an orifice plate is the mass flow, given by the following equation (Kiš *et al.*, 2013):

$$q_m = \frac{C}{\sqrt{1 - \beta^4}} \varepsilon \frac{\pi}{4} d^2 \sqrt{2 \Delta p \rho_l} \quad (3.6)$$

Symbols

C

Parameters

Discharge Coefficient

β	Diameter ratio [$\beta = d/D$]
ε	Factor of expansion
d	Diameter of the orifice
Δp	Differential pressure
ρ	Density of fluid

The discharge coefficient is commonly given by the Reader-Harris/Gallagher equation (Kiš *et al.*, 2013):

$$C = 0.5961 + 0.0261\beta^2 + 0.000521 \left(\frac{10^6 \beta}{Re_D} \right)^{0.7} + (0.0188 + 0.0063A)\beta^{3.5} \left(\frac{10^6}{Re_D} \right)^{0.3} + (0.043 + 0.080e^{-10L_1} - 0.123e^{-7L_1}) \times (1 - 0.031(M'_2 - 0.8M'^{1.1}_2))\beta^{1.3} \quad (3.7)$$

Symbols	Parameters
Re_D	Reynolds number from pipe diameter
$L_1 = l_1/D$	Quotient between the distance of the upstream tapping from the upstream face of the plate and the pipe diameter
$L'_2 = l'_2/D$	Quotient between the distance of the downstream tapping from the downstream face of the plate and the pipe diameter

And with:

$$M'_2 = \frac{L'_2}{1 - \beta} \quad (3.8)$$

$$A = \left(\frac{19000\beta}{Re_D} \right)^{0.8} \quad (3.9)$$

Should the pressure taps be of the flange type:

$$L_1 = L'_2 = \frac{25.4}{D} \quad (3.10)$$

If $p_2/p_1 \geq 0.75$ then the factor of expansion is given by the formula:

$$\varepsilon = 1 - (0.351 + 0.256\beta^4 + 0.93\beta^8) \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{1}{\kappa}} \right] \quad (3.11)$$

κ being the Von Kármán constant.

Orifice plates are, like Pitot Tubes, pressure differential devices - that is to say, they extrapolate the flow speed and flow rate from the imposition of pressure differences in the flow. In the case of orifice plates, this consists in the insertion of flow restricting circular plates into the tube - the reduction in available cross-section causing an increase in flow speed and subsequent drop in pressure. At both ends of said restriction the pressure is registered and, from the difference between registered pressures, the flow rate is deduced.

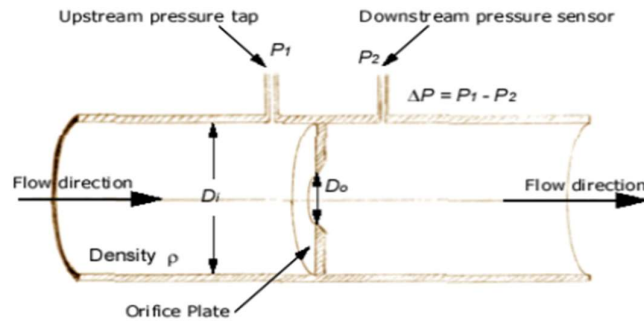


Figure 3.11 - Illustration of an orifice plate. (Mokhatab, 2019)

The orifice plate presents considerable advantages - particularly the thin, concentric, sharp-edge orifice plate - namely its inexpensiveness and accuracy, as well as easiness of installation, use and replacement. They can return reliably precise measurements of a liquids, gases and vapours over a vast range of conditions. Its dimensions and, occasionally, the material chosen for its manufacture (the standard one being stainless steel) are a function of the line size, flowing temperature and differential pressure across it (Lipták, 2002).

The sharpness of the leading edges of the orifice plate is an element of major importance. The presence of friction between the fluid and the metal will cause noticeable disturbances in the flow and induce rather large errors into the measurements (Figure 3.12). An analogous logic applies to pipe roughness and fluid viscosity (reflected in the Reynold's number). The *vena contracta* - that is to say, the flow area where pressure is minimal and the steady, permanent regime flow has a minimum diameter - is a fundamentally inertial phenomenon. Therefore, should the ratio of inertial to frictional forces decrease (that is, should the Reynold's number diminish), there will necessarily be less constriction of the flow and an increase in the flow coefficient of discharge. As such, the use of this device is only advised under certain conditions - namely a Reynold's number between 2000 and 10000.

Is is important that fluid accumulation in the connections between the pipes and the differential-pressure measuring device be avoided. The pressure taps will generally be placed in the horizontal plane of the centreline of horizontal pipe runs. The differential-pressure measuring device will either be coupled closely to the pressure taps or connected by way of a downward sloping pipe dimensioned in such a way as to allow for any eventual gas bubbles to flow back into the line (Lipták, 2002). However, taps may also be installed on the top or the sides of the line. It is common to use condensing chambers, often with downward sloping connections, when the measured gas is steam or vapour.

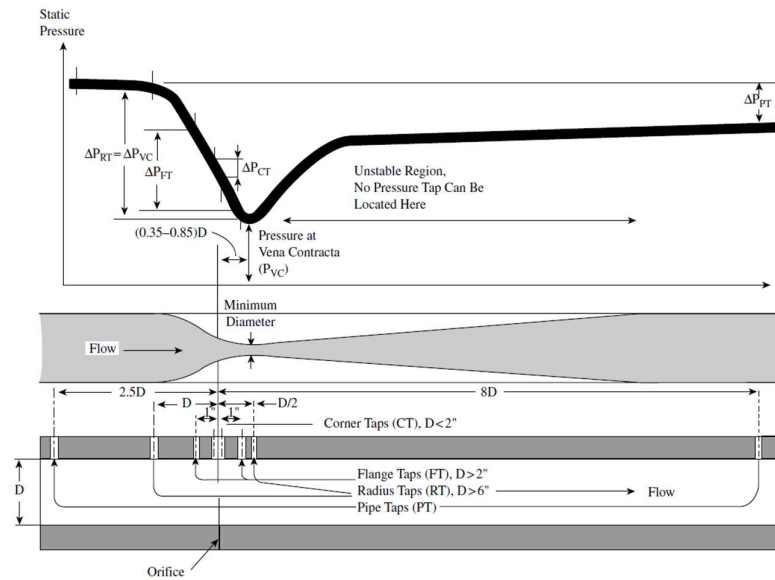


Figure 3.12 - Pressure profile through an orifice plate and the different methods of detecting the pressure drop. (Lipták, 2002)

The most common configurations for differential-pressure taps are: flange taps, *vena contracta* taps, radius taps and corner taps (Figure 3.13).

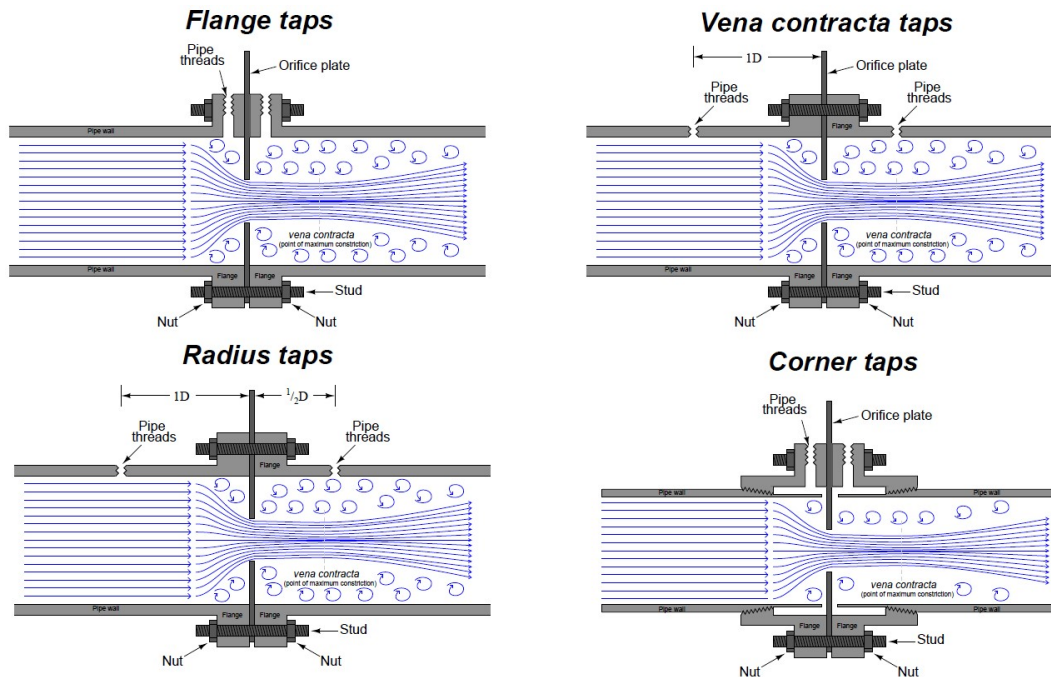


Figure 3.13 - Various configurations for differential-pressure taps. (Jadav *et al.*, 2019)

Despite its various, evident, advantages, it must be said that the concentric, sharp-edged orifice does have some limitations, namely: it is not recommended for slurries, dirty fluids or indeed any flow where solid particles may accumulate near the orifice plate; orifice plates built to withstand corrosion or erosion cannot, generally, operate under harsh conditions and are, thus, unadvised; there might be problems when the fluid is multiphasic, requiring the installation of “vent holes” or the use of a vertical installation; etc (Jadav *et al.*, 2019).

3.4 Oxygen sensor (Lambda sensor)

Simply put, the Lambda Sensor is a device allowing for the continual measurement of the oxygen proportion in a given gas or liquid. It derives its name from the Greek letter λ , used to denote the air-fuel ratio in an internal combustion engine (Equation 3.12):

$$\lambda = \frac{\text{real A/F ratio}}{\text{stoichiometric A/F ratio}} \quad (3.12)$$

These devices were developed in the 1970's by BOSCH under the supervision of Dr. Günter Bauman. Such a development was highly encouraged by the then growing air-quality regulations. These U-shaped tubes were quickly implemented in the automotive industry, particularly by Volvo and Saab. (Shuaishuai *et al.*, 2019). The purpose of this device is, of course, to control the air-fuel ration operating in a combustion engine.

The first two generations of the Lambda Sensor had no built-in heating capacity - and they require high temperatures to function. As the emissions control became ever stricter and, seeing as the device could not function until the combustion engine had been working for some time, a heating rod was inserted into the U-shaped tube in the third generation. Subsequently, the device suffered further upgrades, today being already in its fifth generation. Table 3.11 details the performance of the 5 (so far) produced generations of Lambda Sensors.

Table 3.11 - Oxygen sensor generation and their comparative parameters. (Shuaishuai *et al.*, 2019)

Oxygen sensor generation	Performance Parameters
1 st and 2 nd generation	- No heating time; - Cold start time > 2 min.; - Exhaust emissions cannot be controlled;
3 rd generation	- Cold start time < 1 min.; - Complex preparation process of components at high temperatures
4 th generation	- Cold start time < 15s; - Small size; - High integration; - Fast heating speed;
5 th generation	- Total reaction time < 10s; - Rapid reaction with linear output characteristic; - Measurement accuracy greatly improved;

The introduction of these devices into the automotive industry has allowed for the careful control of the emission of noxious gases, such as NO_x, CO and HC, by maintaining the A/F ratio nearer to the stoichiometric value (Takeuchi *et al.*, 1986). Nevertheless, their use has extended into various other fields, such as iron manufacture, diving and scientific research, to name but a few.

3.4.1 Working principles

The main physical principle behind the Lambda Sensor is described by the Nernst equation. The aforementioned law, named after the German scientist Walter Nernst for its discovery in

1889, relates the reduction potential of an electrochemical reaction to the standard electrode potential, temperature and activities of the chemical species undergoing reduction and oxidation (Vidal-Iglesias *et al.*, 2012).

Fundamentally, the Lambda Sensor is a solid-electrolyte galvanic oxygen concentration cell. A gas-impermeable solid electrolyte - consisting of zirconium dioxide and yttrium oxide - is employed to physically separate the exhaust gas from the reference atmosphere. In spite of the physical separation, this mixture of oxides acts as a near-perfect conductor for the oxygen ions. On both sides, the reference and exhaust atmospheres, catalytically active platinum electrodes are present (Figure 3.14). At the inner electrode the following reaction occurs:

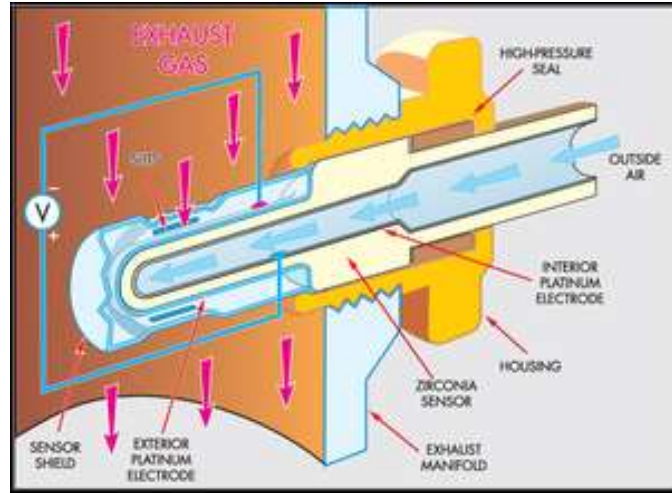


Figure 3.14 - Lambda sensor in operation. (Clarke, 2009)

The resulting oxygen ions will migrate from the side of high oxygen concentration to the side of low oxygen concentration through the YSZ electrolyte conductor: this will originate a potential U on both sides of the YSZ electrodes:

$$U = \left(\frac{RT}{4F} \right) \ln \left(\frac{p_1}{p_2} \right) \quad (3.14)$$

It is this voltage which allows us to make deductions regarding the oxygen concentration - and such data is stored in the computer after passing the circuit board. A rich mixture will generate a voltage of $\sim 0.9V$, whereas a lean mixture of $\sim 0.1V$ (Figure 3.15).

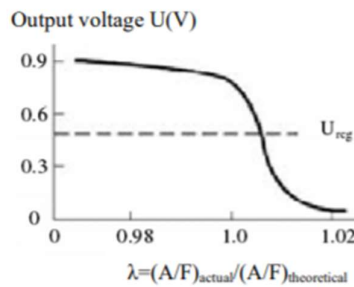


Figure 3.15 - Characteristic curve for voltage output related to A/F ratio. (Shuaishuai *et al.*, 2019)

Chapter 4 Internship Description

4.1 The company

PROVADEMSE (*Procédés Propres Valorisation Dépollution Matières premières Secondaires Effluents et Energie*) is a technological innovation platform from INSAVALOR, an R&D subsidiary from INSA Lyon. This means that PROVADEMSE, in and of itself, is not a juridical entity - it is INSAVALOR which serves as its administrative and financial operator, itself possessing a status of “*Société Anonyme*” (limited-liability company). Certified by the competitiveness cluster AXELERA in 2008, PROVADEMSE has been highly supported since its creation by the Ministry of Industry, DRRT, the Region Rhône-Alpes-Auvergne, the Metropole of Lyon and the FEDER funds.

PROVADEMSE follows the guidelines given by the “*Ministère de l’Enseignement Supérieur, de la Recherche et de l’Innovation*” - to be specific, that a “technological platform” has, as its goal, “the organisation of support to companies operating within a given territory”. Therefore, the technological platform should “put its equipment and expertise to the use of companies through the undertaking of technical assessments and services”. In particular, PROVADEMSE provides support for the development of ecotechnologies, proposes methods or solutions for the treatment, disposal and reuse of waste, as well as for the depollution of soils and sediments. It now has an international presence, taking on projects in Europe, the Maghreb, Western Africa and South America (Pons, 2018).

The company has at its disposal a series of laboratories destined for physico-chemical and ecotoxicological analyses, all located either at the *Campus LyonTech la Doua* in Villeurbanne or *Campus Saint Martin d’Hères* in Grenoble. At the *Campus LyonTech* it is possessed of a storehouse wherein large pilot plants for gasification, together with anaerobic and aerobic digestion, are installed - it is in these pilot plants that the experiments requested by prospective clients are carried out.

4.1.1 History

PROVADEMSE is the result of a fusion, undertaken in 2015, between POLDEN (*Pollution Déchets Environnement*) - a division of INSAVALOR created in 1988 - and PROVADEMSE as it came into being in 2010 as a joint effort of the research institutions EEDEMS and ENVIROHNALP. It is labelled by the competitiveness cluster AXELERA. In 2016 it underwent a visual makeover, which it maintains today. This is summed up in Figure 4.1.

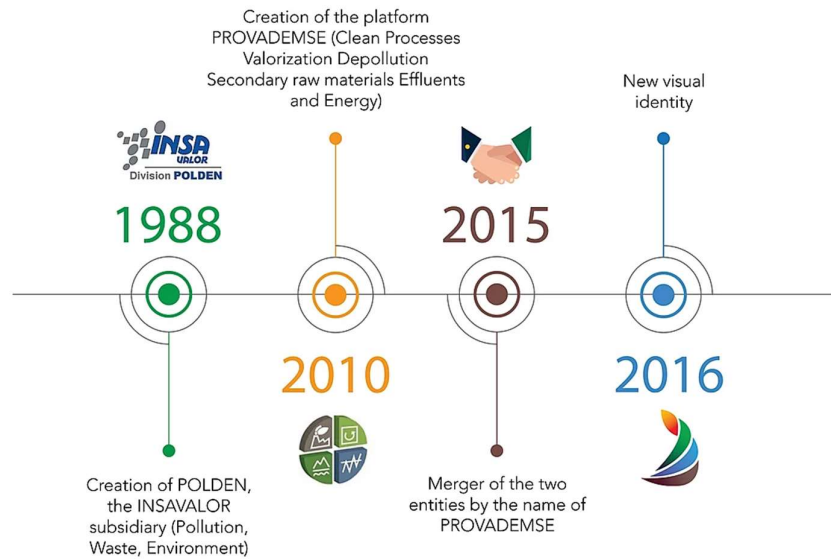


Figure 4.1 - History of PROVADÉMSE's development. (Company website)

Its main focus is the treatment and characterisation of waste. Nevertheless, it also performs duties related to other areas, namely:

- Creation of new materials from residues;
- Using residues to obtain energy;
- Soil depollution;
- Environmental Technology Verification (ETV);
- Ecotoxicology;
- Environmental Characterisation;
- Industrial and Territorial Ecology (EIT - *Ecologie Industrielle et Territoriale*).

4.2 Objectives of The Internship

A gasification trial has many elements circulating in it which must be subjected to rigorous and constant control. This is achieved by the careful placing of many sensors, which will be operating (and storing the data they collect into a computer) all throughout the duration of the experiment. The result is a colossal amount of data. This data must thereupon be processed by the engineer or technician so as to render it readable and exploitable. This process can be long and morose, and it was decided that it would be wise to develop VBA-based Macros to do it automatically in Microsoft Excel.

It is in this context that the internship was to take place: the task being, therefore, to develop said programs, test and then use them on a real experiment to see the results.

Before the programs and their respective development are approached, further context pertaining to the company's facilities and equipment must be provided - such is the aim of this chapter.

4.2.1 What Is VBA?

Before one delves into an elaborate description of the program, it might also be of interest to give a succinct description of what VBA is and what are its uses. VBA means Visual Basic for Applications and it is, as the name suggests, the language Visual Basic as applied to Microsoft Office Applications. Visual Basic itself is derived from the BASIC (Beginner, All purpose, Symbolic Instruction Code) programming language, a high level language developed by Microsoft. BASIC-written programs are created in an integrated development environment (IDE), which means that the programmer can create, run and design programs in a fraction of the time he would otherwise need. The widespread use of this language was accompanied by the development of Microsoft windows graphical user interface (GVI) in the late 1980's - and this in turn would lead to the establishment of the first form of Visual Basic as it exists today.

Visual Basic is the most widely used RAD language. It provides powerful features such as graphical user interface, object-oriented features, error handling, structured programming, etc. It has enormously simplified the development of applications for Windows.

This graphical interface is in fact its greatest trump card. Unlike most programming language, which are exclusively text-based, Visual Basic allows the user to work directly with graphical display and, as such, to develop programs more quickly and intuitively. It has a clear, albeit disciplined, syntax which is easy to test, debug and modify.

With relatively low effort or time expenditure, professional-looking applications can be created. It is especially suited when the developer wishes to focus on user interface (Roper, 2012).

With these characteristics in mind, it is no wonder that VBA was the chosen language to develop our programs - which would be integrated into the very powerful tool Microsoft Excel.

4.3 Description of the Gasification Plant and its Components

The installed gasification plant - named GASCLEAN® - possesses a power output of 100 kW. It was initially conceived and patented by the COGEBIO society. In this initial version it was not well adapted to the treatment of waste, having been designed with “pure” biomass in mind, and was, ergo, not well suited to PROVADEMSE’s waste recycling or R&D purposes. As such, it was the target of significant modifications to better suit it to its intended goals.

The gasification plant is located within a large warehouse in the *Freyssinet* building of the INSA Lyon Campus. Its working components occupy a two-tier platform, with the gasifier and air injector on the ground level (Figure 4.2) and all other components installed on the upper level (Figure 4.3).



Figure 4.2 - Ground-level at PROVADEMSE’s gasification plant. The gasifier can be seen on the left picture.



Figure 4.3 - Gasification plant upper-tier. This is where the technicians and engineers survey the trial.

Before giving a general explanation of its functioning, a more detailed overview of each component will be given. A schematic detailing the overall structure of the plant is shown in Figure 4.4.

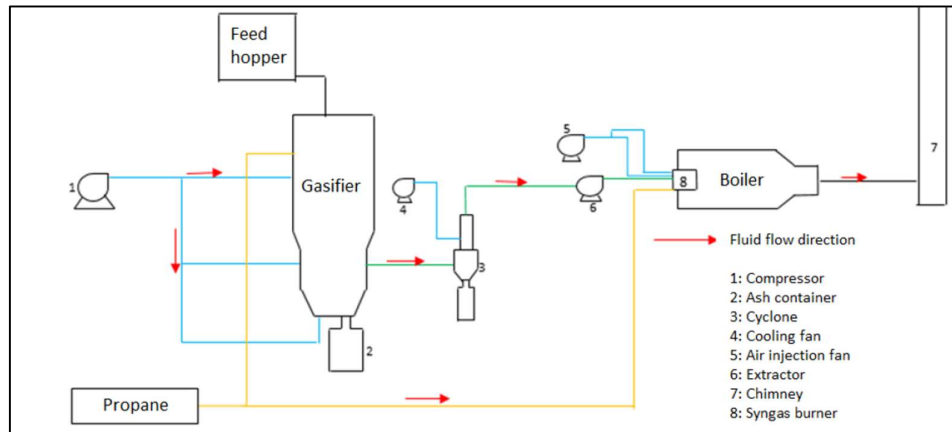


Figure 4.4 - Simplified schematics of the gasification plant. (Coulibaly, 2008)

The gasification plant is composed of various components, namely:

- Circuit-control board
- Control computer
- Feed hopper
- Gasifier
- Ash-bin
- Cyclone
- Air-injection fan
- Air heat-exchanger
- Syngas extractor
- Gas burner
- Boiler
- Fumes extractor
- Chimney
- Water-cooling circulation system
- Air heater

One will refrain from mentioning the various sensors for the moment. The computer contains a software which not only contains a graphic interface (Figure 4.5) allowing the users to keep close attention to how the trial is going, but also to adjust various operating parameters by simply inputting them into it.



Figure 4.5 - Software graphic interface.

4.3.1 Circuit-Control Board

This equipment (Figure 4.6) controls the electrical energy feeding of the whole installation. It has an automaton allowing for the automatic working of the various components of the machine as well as the adjustment of the various injected airflows and/or other controlled parameters. It is connected to a computer (Figure 4.7) where data obtained from the various sensors is stored within specific time intervals (temperature, pressure, O_2 concentrations, flowrates, etc.).

The circuit-board door contains a screen which displays information about the trial in real time. The buttons on the door can stop the trial in case of emergency - as well as restart it.



Figure 4.6 - Circuit-control board.



Figure 4.7 - Computer connected to the circuit-board.

4.3.2 Feed Hopper

Here (Figure 4.8) the soon-to-be-treated waste/fuel can be stored and, when so desired, fed to the gasification reactor by the action of a hydraulically acted scraper. This hopper can store up to 1m³ of matter. It has a hatch, which is held tightly shut by another hydraulic system, ensuring its imperviousness.



Figure 4.8 - The gasification plant's feed hopper, with the hatch closed.

4.3.3 Gasification Reactor

This pilot-scale gasifier, of the co-concurrent fixed-bed type, measuring 2.40m in height, standing 1.15m from the ground, has the capacity to treat 25 kg/h of waste. Its functioning is similar to all such gasifiers. Four important thermochemical processes take place within the reactor: drying, pyrolysis, partial oxidation and reduction. Though there is no actual physical separation between the zones where these processes occur, they are nevertheless clearly delimited (Figure 4.9). Air is injected into the gasifier at 10 different points, 8 of which located in the combustion zone - the remaining 2 being in the drying and reduction zone. The injection of air is carefully controlled by the presence of a Pitot tube (Figure 4.18).

Three manual valves are present which may be used to shut and isolate the reactor should the need arise (they are connected to the feeding, ash-removal and syngas extraction zones, specifically). Another valve, this one actioned pneumatically, permits the immediate evacuation through the chimney, for security reasons, of the gases contained within.

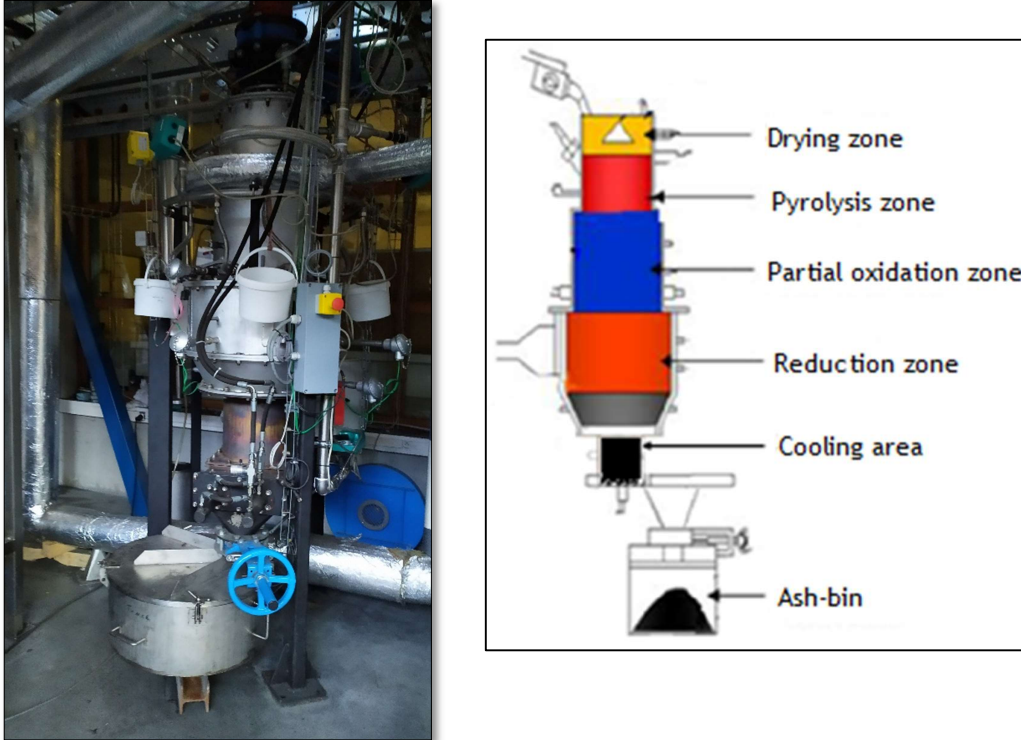


Figure 4.9 - PROVADEMSE's gasifier (left) and illustration of the various internal zones (right).(Ruje, 2015)

Below these 4 reaction zones a cooling area was added, aiming to protect the ash removal system from damage resulting from the residues' high temperature.

4.3.4 Ash Removal System

Clearly visible below the gasifier is the ash storage bin. At the bottom of the reactor, a hydraulic cylinder moves a scraper which rids the reactor of the accumulated ash. This method presents an advantage over the more typical grill-based system, allowing for the easy removal of larger particles.



Figure 4.10 - Ashbin at bottom of gasifier (left).

4.3.5 Cyclone

Upon leaving the gasifier, the syngas will often transport volatile particles with it. Therefore, before proceeding to the boiler, it will pass through a cyclone (Figure 4.11), whereupon it will be cleaned and purified. The fluid is made to enter at an angle tangential to the cylindrical equipment's wall, creating a vortex within it, which in turn will impose a rotating movement on the cylinder. This exposes the particles to a centrifugal force, making them move towards the inner wall of the equipment. There they will gradually lose their speed due to the wall's friction force and will finally fall into the dust-collecting bin. The fluid, by contrast, will travel downwards along the wall until it is able to exit through a vertical tube. The cyclone's opening is controlled by the action of a manual ball valve.

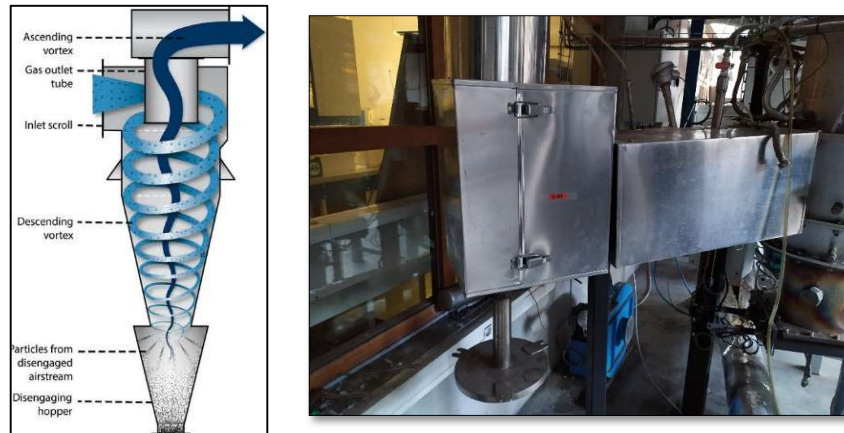


Figure 4.11 - Cyclone (right) and schematics of its inner workings (left) (Metso Corporation®).

4.3.6 Cooling Heat Exchanger

The syngas extraction fan cannot tolerate temperatures much higher than 400°C. This being the case, the syngas must be cooled prior to its extraction. This is achieved by air circulating in an enveloping annular space - an heat exchanger. This cooling air, injected by a fan, is capable of lowering the gas' temperature from 600°C down to 400°C. The cooling-air fan (Figure 4.12) is a CAHP model from AEIB, with a 0.75kW power capacity, rotation speed of 2895 rpm and an efficiency of 51.3%.



Figure 4.12 - Air injection fan - injects air into the heat exchanger to cool the syngas.

4.3.7 Extraction Fan

This fan (Figure 4.13), model CAHP HT, also from AEIB, serves to extract the gas from the gasifier and introduce it into the boiler. It can withstand temperatures up to 400°C, has a power output of 3 kW, rotation speed of 2820 rpm and a global efficiency of 52.4%.



Figure 4.13 - Syngas extraction fan. The blue engine responsible for its working can be seen next to it, as well as the blue manual valve which initiates the extraction.

4.3.8 Boiler

This THERMITAL® brand gas boiler, which produces heat by burning the syngas - to minimise waste, the heat from the released combustion will be harvested - is composed of a mixed burner, a pilot light, a flame detector (DUNGS brand) and a lambda probe (Lambda Check).



Figure 4.14 - Boiler where the syngas is burned to acquire energy. All the participants in the combustion are injected through the burner, seen here at the boiler entrance.

The combustion necessitates the introduction of air into the mixture. This is achieved by the action of an air-injection fan, displayed in Figure 4.15. This fan is also a CAHP model, also by AEIB, possessing a power output of 1.5 kW, rotation speed of 2900 rpm and 49.3% efficiency.



Figure 4.15 - Fan responsible for injecting air into the boiler.

4.3.9 Burner

Special attention must be paid to the burner (Figure 4.16), designed and patented by COGEBIO®. It is called a “mixed burner” as it permits the simultaneous burning of syngas and a natural gas, in this case propane. As the syngas has an unstable flowrate, without the presence of another combustible it becomes very difficult to maintain a steady functioning of the boiler. Air is pumped into the burner by a primary and secondary inlet. The former is aimed at igniting the mixture, whereas the latter is meant to manage the intensity of the flame, as well as the excess of air which might be present in the combustion smokes.

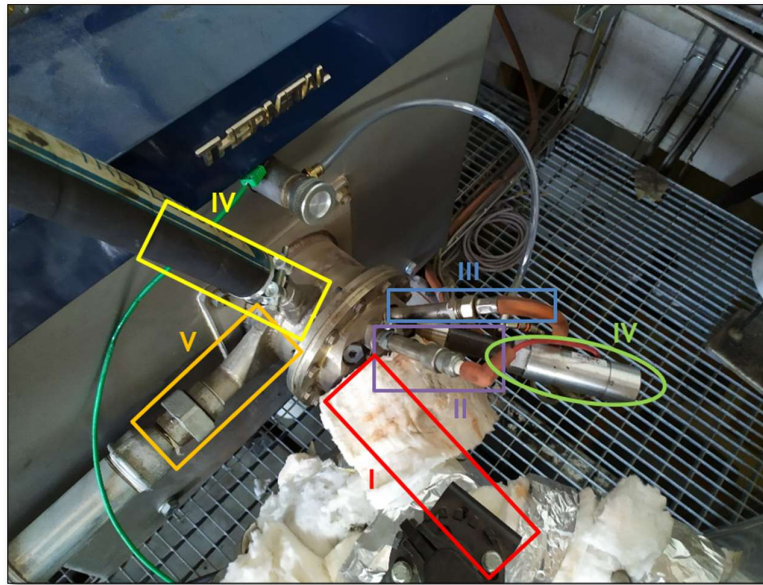


Figure 4.16 - Mixed burner, with its various inlets identified in Table 4.1.

Table 4.1 - Burner injection inlets and flame detector.

Number	Component
I	Syngas inlet
II	Pilot light
III	Propane inlet
IV	Flame detector
V	Primary air inlet
VI	Secondary air inlet

4.3.10 Water Cooling Circuit & Air Heater

Prior to its release into the atmosphere, the combustion fumes from the boiler are cooled by an adjacent water closed-circuit (Figure 4.17). This water releases this heat through an air heater, located outside the warehouse (Figure 4.18). Said unit can withstand fluid temperatures up to 110°C, and has a power of 560 W.



Figure 4.17 - Circuit for water cooling. The water is itself cooled in the air heater stationed outside.



Figure 4.18 - Air heater.

4.3.11 Fumes Extraction System + Chimney

Originally, the fumes were evacuated from the plant by natural convection. However, this was found to be an inefficient method, and an extraction system - which relies on an exhaust fan - was installed (Figure 4.19). It is possible to choose which of these two systems one wishes to use by actioning the valves accordingly.

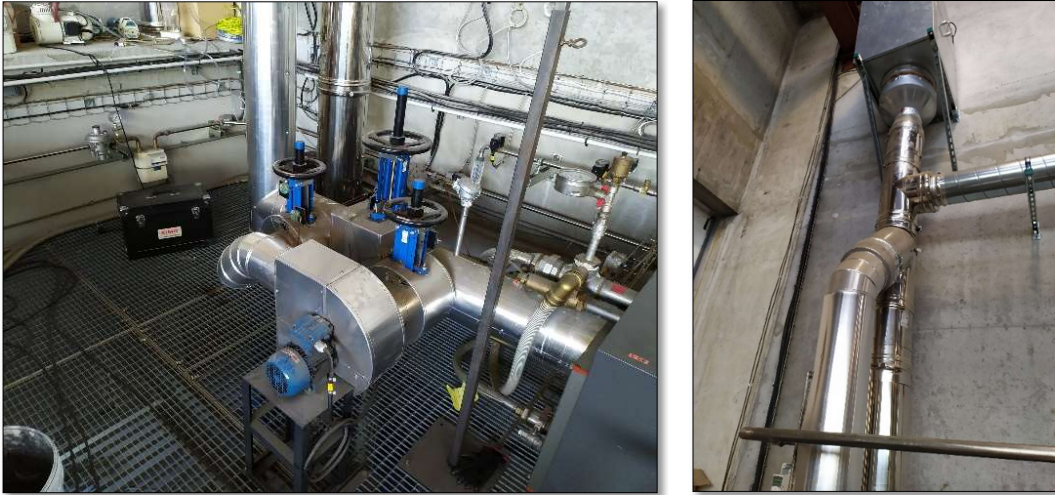


Figure 4.19 - Fumes extraction system (left) and chimney (right).

Once the fumes cross this area, they escape into the atmosphere through the chimney. This is a double pot chimney, with external and internal diameters of 255 mm and 220 mm, respectively. It contains a hatch to allow for the retrieval and analysis of fume samples.

4.4 Gasification plant sensors

A wide array of sensors is installed throughout the gasification plant. These will register various values which are afterwards stored in .csv files. As these sensors are the source of the data which will be processed with the devised program, it is important to have some awareness of how they work and where they are.

4.4.1 Thermocouples

In this gasification plant the thermocouples are all from TC Direct. They are either type T, K or N, with an Inconel wiring, 300mm length and a 15.9mm diameter. They can withstand up to 1100°C. There are two kinds of thermocouples in operation: the ones designated with the letters TT register and store the temperature values they measure, whereas the ones with the letter TSH (as the one shown in Figure 4.20) merely act as safeguards, shutting down the machine if a certain temperature limit is detected. They are listed in Table 4.2.

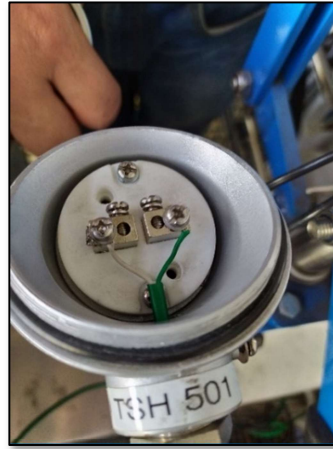


Figure 4.20 - Thermocouple after having hatch removed. This one controls the syngas temperature.

Table 4.2 - Thermocouples installed throughout the gasification plant.

SENSOR NAME	LOCATION	TYPE
TT050	Top of gasifier	T
TT051	Gasifier: reduction zone	K
TT052	Gasifier: pyrolysis zone	K
TT053	Gasifier (wall): oxidation zone	N
TT054	Annular zone syngas	K
TT400	Air Inlet Gasifier	T
TT500	Syngas Outlet Gasifier	K
TT501	Syngas Boiler Inlet	K
TT600	Air Exchanger Inlet	T
TT601	Air Exchanger Outlet	T
TT800	Water Boiler Inlet	T
TT801	Water Boiler Outlet	T
TT900	Fumes	T

4.4.2 Flowrate: orifice plate and Pitot tube

As explained in Chapter 3, both types of flowrate detectors use imposed pressure gradients to deduce the speed - and, therefore, flowrate - of the travelling fluid. There are automatons connected to the sensors which perform the necessary calculations automatically and store the results directly. They are displayed in Figure 4.21 and enumerated in Table 4.3.

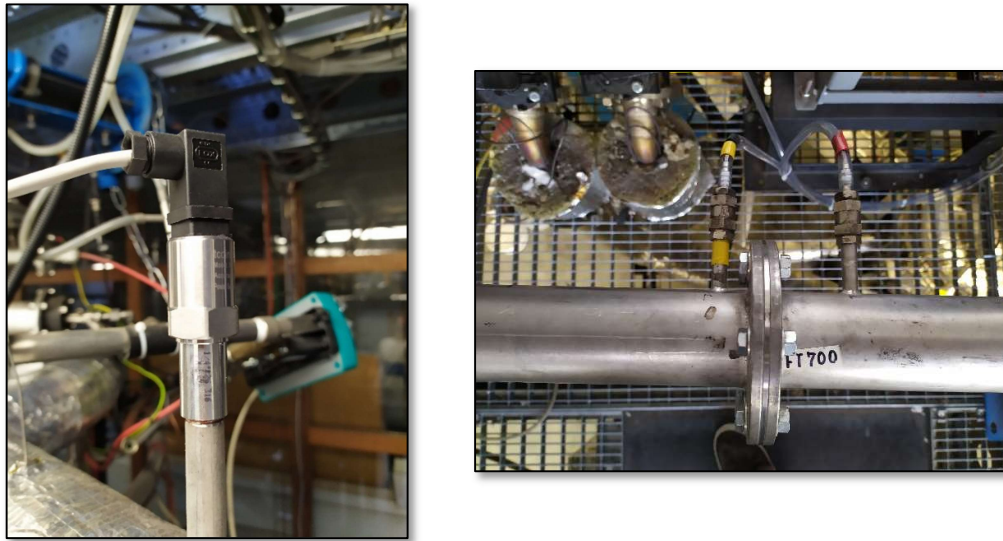


Figure 4.21 - Pitot tube controlling the air injected into the reactor (left). Orifice plate measuring air flowrate into the boiler (right).

Table 4.3 - Flowrate sensors in the gasification plant.

SENSOR NAME	LOCATION	TYPE
FT401	Air (Pyrolysis)	Pitot Tube
FT402	Air (Oxidation)	Pitot Tube
FT403	Air (Reduction)	Pitot Tube
FT500	Syngas	Orifice Plate
FT600	Air (Heat Exchanger)	Orifice Plate
FT700	Air Boiler Combustion	Orifice Plate
FT801	Water (Cooling)	Pitot Tube

4.4.3 Pressure Sensors

These are integrated into the machine. They are equipped with a circuit which converts pressure into a normalised output signal (4-20 mA) using two wires (Figure 4.22). They are made with inox and have a cylindrical G ¼" male. The sensors have a response time of 0.5 seconds.

The head loss within the gasifier is a very important parameter to study. It allows not only to adjust for the syngas extraction but also to search for issues within the reactor (particle agglomeration, bed fracture, etc.). The pressure sensors are listed in Table 4.4.



Figure 4.22 - Pressure sensor converter (centre).

Table 4.4 - Pressure sensors in the gasification plant.

SENSOR NAME	LOCATION
PT050	Top of Gasifier
PT051	Reduction area
PT500	Syngas (exiting gasifier)
PT501	Syngas (entering burner)
PT900	Fumes

4.4.4 Lambda probe

The Lambda probe (Figure 4.23), from Lambda Check®, is located (Table 4.5) at the very exit of the boiler so that it can have as precise a reading of the combustion's fumes' CO₂ concentration as possible.

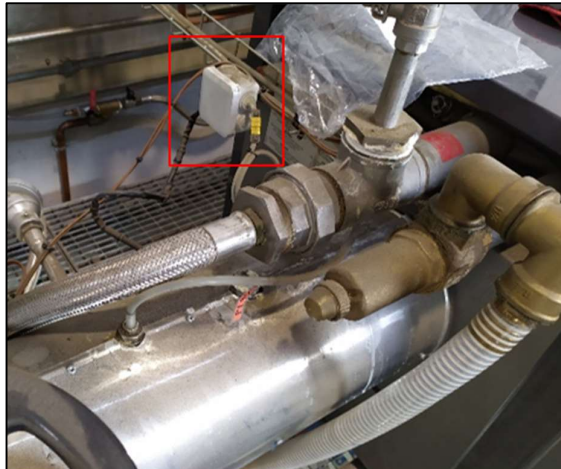


Figure 4.23 - Lambda probe (highlighted in red) at the boiler's outlet.

Table 4.5 - Lambda probes in the gasification plant.

SENSOR NAME	LOCATION
AT080	Exit Boiler

4.4.5 Weight Sensor

The 4 legs of the feed hopper are equipped with pressure-sensitive weight sensors (Figure 4.24). The platform on which the feed hopper stands is prone to vibration when people are walking on it - this can induce small fluctuations in the registered values. Table 4.6 lists the weight sensors present in the facility.



Figure 4.24 - One of the four weight sensors installed in the feed-hopper's legs.

Table 4.6 - Weight sensors in the gasification plant. It should be noticed that, despite there being 4 such sensors, they are counted as only one - it is the average value from the 4 sensors which is stored.

SENSOR NAME	LOCATION
WT010	Feed Hopper

4.5 General Functioning of the Machine

At the very beginning of the gasification trial a tissue containing an inflammable fluid must be laid over the char bed to burn it and kickstart the process. The feed hopper feeds the gasification reactor by means of an automated scraper. This scraper is moved by the action of a hydraulic pusher, itself activated by the engine shown (Figure 4.25).



Figure 4.25 - Engine (left) that starts the hydraulically-acted (right) scraper which feeds the gasifier.

The reactor is capable of treating up to 25 kg/h of material. Should there be any clogging of the feeding tube (Figure 4.26), a detector will return a signal to the circuit board, this

malfunction flashing in the computer, and stop the process. Should this happen the tube must be unclogged by inserting a long metallic rod into it.

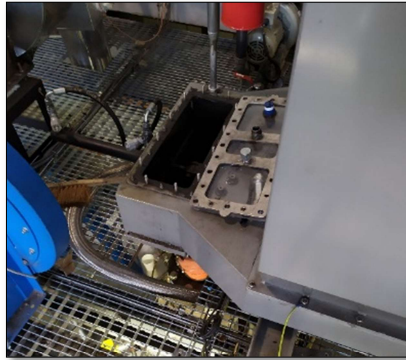


Figure 4.26 - Chute into which the fuel is fed. It must occasionally be manually unclogged.

This gasification plant is capable of using several types of material, provided the particles entering have specific conditions:

- Main fraction of the matter (>80% of input mass): $3.15\text{mm} \leq D_{\text{particle}} \leq 45\text{mm}$
- Fraction of finer matter (<12% of input mass): $D_{\text{particle}} \leq 3.15\text{mm}$
- Maximum length: 120mm
- Relative humidity <20%

Upon entering the gasification reactor (Figure 4.27), the material will undergo the various aforementioned thermochemical treatment processes.



Figure 4.27 - Top of gasifier, with connection to the feed hopper (left). Various air insertions into the gasifier, as well as regulators and sensors (right).

At the bottom of the reactor, another automatically actioned scraper will extract the ash resulting from the process into an ashbin, at a rate of 0.5 kg/h of ash. While the process is ongoing, the various sensors are busily registering all the relevant data and sending it into the circuit board, which then sends it into the computer (Figure 4.28).



Figure 4.28 - Large amount of sensor data converters next to the gasifier (left). They collect measurements from the considerable quantity of sensors mounted on this part of the plant (right).

The extraction of syngas from the gasifier is controlled by actioning the manual valve presented in Figure 4.29. It is extracted from the reactor through the action of an extractor fan (Figure 4.13) which will regulate its speed in accordance with the pressure registered at the top of the reactor. The two displayed magnetic detectors (Figure 4.29) detect its position. The syngas exits the reactor at approximately 600°C. It must be cooled into the more manageable temperature of 400°C by passing through a heat exchanger. This process is laden with sensors, their signal convertors fitted to the wall nearby (Figures 4.28). Afterwards, it will pass through a cyclone where it will be filtered of its larger particles.

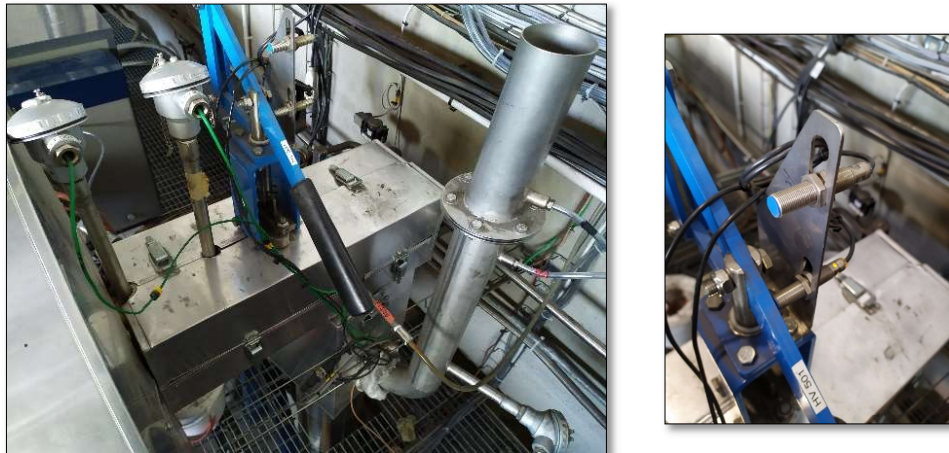


Figure 4.29 - Manual valve which must be actioned to start syngas extraction (left). To its left two thermocouples, which measure the syngas' temperature, can be seen. To its right is the chimney from where the air from the heat exchanger is expelled after cooling the syngas. The valve is acted by magnets which detect its presence (right).

Once it reaches the burner, the syngas will be ignited. Occasionally, there will not be enough syngas to ensure a reaction, in which case propane will be sent into the mixture (Figure 4.30). Even so, the burner is equipped with a flame detector which will flag and stop the process should a flame fail to ignite. The heat resulting from the combustion in the boiler will be transferred to the water circuit running through it or be dispersed in the resulting fumes. The fumes are evacuated through the chimney, although the operators can have them go through an alternate path so as to have it analysed - they have to activate the different valves, actioned by an induction system (Figure 4.31). Upon leaving the boiler, the fumes are analysed by a

Lambda probe, and the concentration of oxygen detected will automatically determine the air mixture sent into the burner by the secondary inlet.



Figure 4.30 - Propane injection line (left). The flowrate is measured directly in the flowmeter (right).

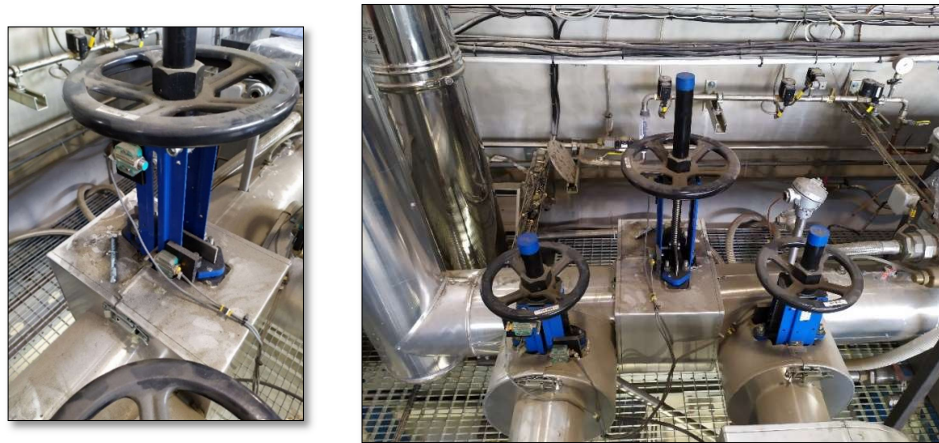


Figure 4.31 - Fume extraction system with two alternate paths (right). The valves are open or close the tubes. An inductor detects their position (left).

The fumes emitted by the boiler will be cooled by a water circuit and then released by the chimney. Some will be collected for analysis.

4.6 Conversion into .csv files

The values registered by the sensors are stored into .csv files. At the end of each gasification trial, a folder will be created containing the accumulated data from all the sensors. It is from this data that analysis of the experiment proceeds.

Given the sheer number of sensors, as well as the long working hours, the amount of collected data is gigantic and will require processing before being used for analysis.

Archives 2020.03.10

	A	B	C	D	E
	VarName	TimeString	VarValue	Validity	Time_ms
1	Débit FT600	10/03/2020 09:15	12.60017	1	43900386010
2	Débit FT600	10/03/2020 09:15	20.20522	1	43900386068
3	Débit FT600	10/03/2020 09:16	6.735074	1	43900386127
4	Débit FT600	10/03/2020 09:16	6.735074	1	43900386186
5	Débit FT600	10/03/2020 09:16	8.248749	1	43900386244
6	Débit FT600	10/03/2020 09:16	0	1	43900386303
7	Débit FT600	10/03/2020 09:16	0	1	43900386361
8	Débit FT600	10/03/2020 09:16	4.762417	1	43900386420
9	Débit FT600	10/03/2020 09:16	8.248749	1	43900386478
10	Débit FT600	10/03/2020 09:16	15.06009	1	43900386537
11	Débit FT600	10/03/2020 09:16			
5747	Débit FT600	10/03/2020 18:48	0	1	43900783505
5748	Débit FT600	10/03/2020 18:48	6.288379	1	43900783564
5749	Débit FT600	10/03/2020 18:48	6.288379	1	43900783623
5750	Débit FT600	10/03/2020 18:48	12.57676	1	43900783681
5751	Débit FT600	10/03/2020 18:48	6.288379	1	43900783740
5752	Débit FT600	10/03/2020 18:48	9.942801	1	43900783799
5753	Débit FT600	10/03/2020 18:48	7.70166	1	43900783858
5754	Débit FT600	10/03/2020 18:48	4.446556	1	43900783917
5755	Débit FT600	10/03/2020 18:48	9.942801	1	43900783976
5756	Débit FT600	10/03/2020 18:49	0	1	43900784035
5757	Débit FT600	10/03/2020 18:49	0	1	43900784093

Figure 4.32 - Folder with the .csv files containing all the data collected from the sensors after a gasification experiment.

Chapter 5 Data-processing Program

Now that we have a clear understanding of the gasification plant, its sensors and its workings, it is time to delve into the main objective of the internship.

As was previously alluded to, the amount of data returned from the sensors is much too voluminous and is, often, impossible to read or exploit directly. The first part of the internship required the fine-tuning of a VBA-based program which would automatically process this data. The proper functioning of this program was a necessary preliminary step to obtain a satisfactory analysis of the experiments.

Though the foundational structure of the program already existed, it still contained a few bugs and did not completely perform its objectives to a satisfactory extent. As such, several modifications were proposed and carried out, both in terms of pure performance as in turning the program more intuitive and user-friendly, so that anybody would be able to use it with ease.

As mentioned, the fine-tuning of this program was the prelude to the creation of a new program, the latter having the objective of analysing the processed data. From these analysis conclusions can be drawn regarding the gasification trial.

It must be said that these two programs are of quite dissimilar natures, and, as such, the approach given to each task was very distinct. Therefore, they will be treated in different chapters.

5.1 Context for the program's development

When a sensor in the gasification plant detects the specific quantity it was conceived to measure, it stores its readings into a .csv file. These readings will be taken at specific time intervals, which will vary according to the sensor (for instance, pressure sensors generally record a value at every second whereas temperature sensors will do so at every 5 seconds). As the gasification trials will often last a whole day, it is no wonder that these .csv files will commonly contain tens of thousands of values.

It is then unsurprising that these values are, in their raw form, often unreadable, given the immense amount of statistical noise they register. As an example, take Figure 5.1 containing the value dispersion for the cooling water flowrate during a given trial:

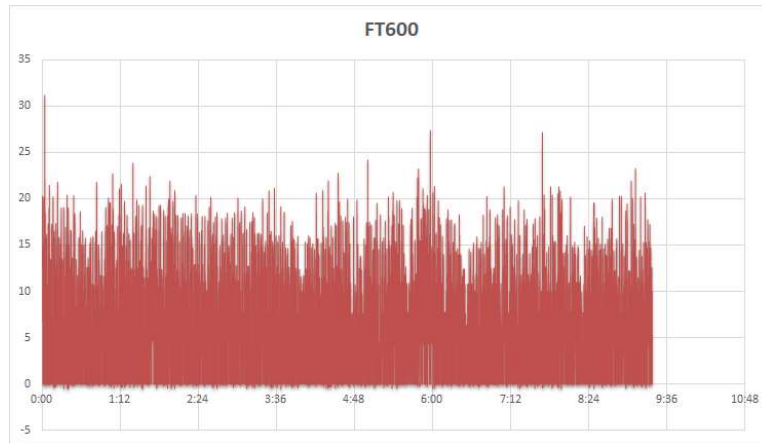


Figure 5.1 - Results registered for the cooling water flowrate (Nm³/h) throughout a gasification trial.

What one hopes to obtain is represented by the curve in Figure 5.2:

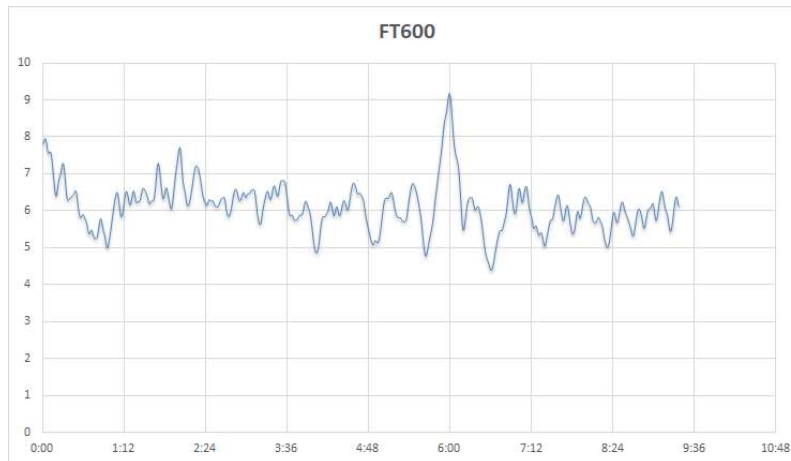


Figure 5.2 - Curve obtained after submitting the data to treatment.

This last curve is achieved by a smoothing of the registered data, as well as the homogenisation of the time intervals at which the sensors' values have been returned.

This had to be done by the engineer by hand: that is to say, he would select the data stored in the .csv files, harmonize its time values and use various excel functions to progressively render the curves readable (special emphasis was given to the use of the Two-Period Moving Average trendline). Given the large numbers of .csv files and the constant process of trial-and-error, this could take up to several hours of the engineer's time. Therefore, the idea was had of creating a series of Excel Macros to do these processes automatically.

Prior to the internship's debut at PROVADEMSE, a rough but working version of this program was already present. The task was to perfect it.

5.2 Structure of the data-processing program

The program as it existed was largely the work of previous interns - Jenny Paola Ruje (2015), Maria Margarita Sierra (2016) and Elie Lacombe (2017) - each giving their own contribution.

As much of the original program's structure was kept, an explanation of its prior main objectives and working processes will still be applicable to the current version. Initially only one Worksheet was permanently available, the Start Worksheet (Figure 5.3), wherein all the Macro-executing buttons were located. At the bottom of this interface was a button which would reset the program - thereby eliminating all other sheets.

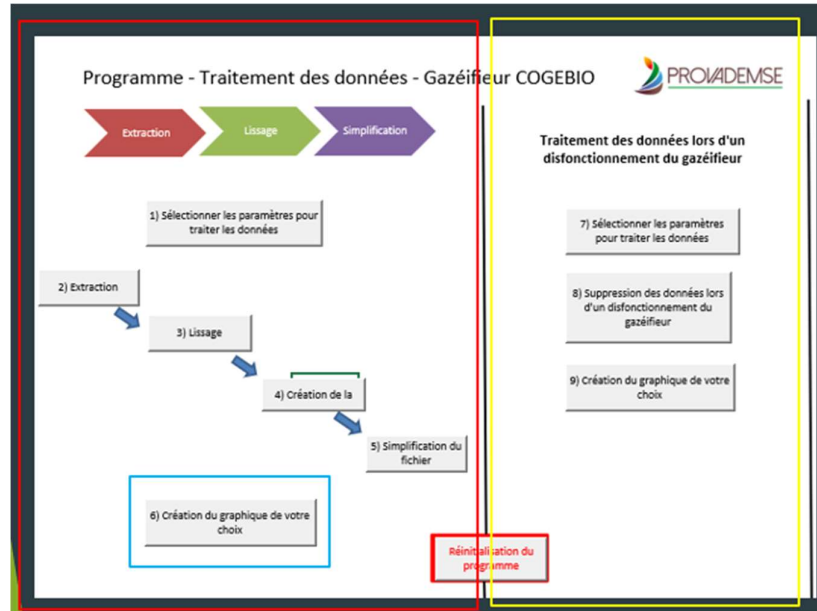


Figure 5.3 - Start Worksheet, which serves as the main User Interface. Highlighted in red is the first part of the process; in yellow the data elimination step and in blue the button for creating comparison graphs.

The program had two main functions:

1) Extract all the “.csv” files from whichever folder they were stored in, smooth their values and copy them into a single worksheet containing an ensemble of all the information - at the end of this first part of the process all of the worksheets would be cleansed of superfluous information so as to render the file lighter;

2) Delete, from said ensemble of information, the values registered during undesired time intervals - for example, when there was a machine malfunction and the sensors kept registering values regardless. This was done by choosing a minimum or maximum syngas flowrate that must be recorded: any time intervals containing values outside this interval would be disregarded. This follows from the fact that, in case of a machine malfunction - whatever the cause - the syngas flowrate will be much reduced or nullified almost immediately.

For ease of communication, these will be spoken of as “program modules”, the first one being denominated as “Processing module” and the second as “Deletion module”. As can be seen in Figure 5.3, the buttons 6 and 9 permit the creation of graphs comparing the effects of both modules on the raw data.

5.2.1 Processing module

The first thing required of the program's user would be the input of certain essential parameters:

- The location of the folder containing all the “.csv” files

- The number of averaging (or smoothing) cycles to be undertaken. Heretofore referred to as Smoothing Number (N_s)
- The time step at which to store the processed data. That is, once it was smoothed, the data would have to be copied into a data sheet containing all of the information (called Raw Data Sheet from here onwards). The time steps for the Raw Data Sheet would be input by the user - this parameter was called, rather simply, Time Interval (t).

Once all of the parameters had been stored, the user would initiate the process by clicking Extract. This button would activate a Macro which would open the indicated folder and copy all .csv files into new Worksheets bearing the same names. The Smoothing process would then take place in these new Worksheets.

The Smoothing process is the most critical part of the whole program. As such, it will be the target of particular attention.

5.2.2 Smoothing Process - initial version

This part of the program would be launched by clicking on its respective button. If the program found that there was no data to be smoothed in a certain Worksheet, or if that particular sensor's time-step was inferior to the one demanded by the user, said Worksheet would be deleted.

The Smoothing Macro would perform a series of cycles of values-averaging, as displayed in Table 5.1. At the edges of the data columns the averaging would follow distinct rules, but for the most part the program would simply do the following calculation (Equation 5.1):

$$V'_i = \frac{V_{i-2} + V_{i-1} + V_i + V_{i+1} + V_{i+2}}{5} \quad (5.1)$$

With “i” being the row number and “V” representing the value post-cycle. At the first and last rows, the program just copied the value directly (meaning that $V'_1 = V_1$). At the very second and first-to-last rows the averaging would only use three values. That is (Equation 5.2):

$$V'_i = \frac{V_{i-1} + V_i + V_{i+1}}{3} \quad (5.2)$$

Table 5.1 - Effect of the Smoothing Process on the data after 3 cycles - 3 new columns were written.

1	2	3
18	18	18
18	18.13333	18.16444
18.4	18.36	18.36267
18.6	18.56	18.53867
18.8	18.76	18.704
19	18.88	18.832
19	18.96	18.928

These mathematical operations would be executed directly in a newly created column to the right of the latest column. In other words, with a Smoothing Number of 10, 10 columns containing the results of the successive averaging cycles would be created.

5.2.3 Creation of Raw Data Sheet

Having smoothed the values, a new Worksheet is created. The time columns (both absolute and relative) have a time step equivalent to the one inputted by the user at the start. In each of the extracted and processed Worksheets (corresponding to each .csv file), the value from the last smoothing cycle is copied (using t as a selecting time-step) into an adjacent column, and from there copied into a new column in the Raw Data Sheet, this column having the same name as the .csv file from whence the copied value comes.

By now the Excel file will have become rather heavy, and a function exists which rids it of superfluous information (for example, the values obtained from the various averaging cycles). This is the Simplification function.

Once this Macro has been run, the first module will have been finished - the Raw Data Sheet being its intended product.

To observe the effect exerted by the Smoothing process, graphs can be created which compare the values from the .csv files to the ones in the Raw Data Sheet. The timescale used for these graphs will also come from the time-step inputted by the user.

5.2.4 Deletion Module

To use this module the user would, first, again be asked to input the same fundamental parameters (Smoothing Number and Time Interval).

Afterwards, he would be asked to define a syngas flowrate considered sufficiently tenuous to suggest a machine malfunction or an aberrant registered value. A new Worksheet is copied directly from the Raw Data Sheet, named Flagged Data Sheet. The program would compare this defined value to all the registered FT500 (syngas flowrate sensor) values in the Flagged Data Sheet and, if they were inferior to it, flag them by highlighting the whole row in yellow. The program then informed the user of how many time intervals had been flagged. One stresses the fact that several flagged timesteps are counted as only one-time interval. The user would then be presented with the flagged intervals and asked to decide whether or not to delete them (Figure 5.4). The program would then make copies of every Worksheet extracted from the .csv file, giving them the prefix "Sup", and erase the selected time intervals from them (Figure 5.5). This process would end with the creation of another Worksheet - the Suppressed Data Sheet - containing the same values as the Raw Data Sheet except for the ones marked for deletion.

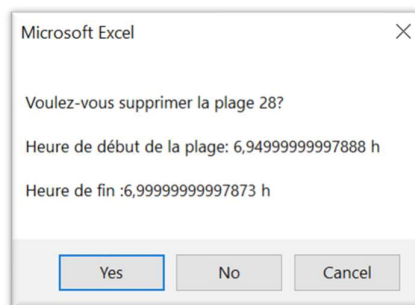


Figure 5.4 - Message Box asking whether the user intends to delete a specific interval. This Message Box would appear for every single detected interval.

Again, a button permits the comparison of the values in the Suppressed Data Sheet and the ones in the “Sup” Worksheets (Figure 5.5).

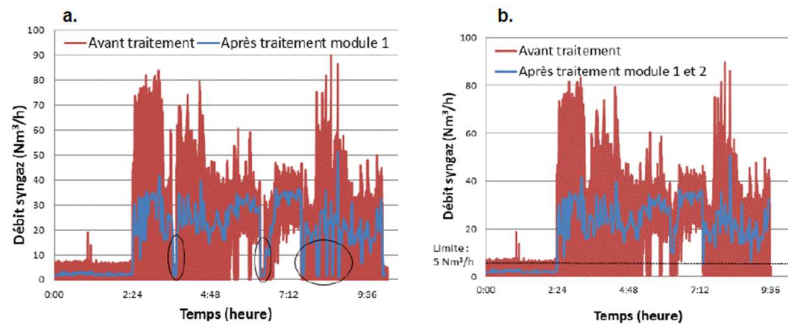


Figure 5.5 - Comparison of smoothed data curves, in blue, pre-deletion (left) and post-deletion (right). (Lacombe, 2017)

5.3 Problems with the previous version of the program

The program as it existed at the internship’s beginning was already capable of performing the task for which it was conceived. Nevertheless, it had several running issues and, due to not being sufficiently fine-tuned, was still not in use. These issues were:

- Slow smoothing

As the program had to constantly write the results of each averaging cycle into the rightmost column to the previous values, this phase of the program could be very computationally expensive. It would, of course, depend on the user’s computer’s processing power, but, for example, it would take an average of 10 minutes per smoothing for a previous intern (Lacombe, 2017).

This was mostly caused by the writing of the values, not the calculations themselves, which the software performs quite quickly. This also meant that the Smoothing Number had a tremendous impact on the amount of time it took to complete the smoothing process - if we had a Smoothing Number of 20, 20 new columns would have to be written for each Worksheet, which would yield a grand total of hundreds of thousands of new values to be written into the Excel-file.

This was, by far, the biggest issue with the program and a solution for it was the most important part of the internship.

- Unsatisfactory reproduction of Two-Point Moving Average Trendline

The over-reliance on the Smoothing Number had several issues, some of which have already been mentioned. Another was that it did not reproduce, satisfactorily, the effect exerted by the Two-Point Moving Average trendline function. The lines would still have many “local” fluctuations and would rarely be as smooth as desired. Not only that, Smoothing Numbers below 10 would rarely be sufficient. This can be seen from the Smoothing studies done by a previous intern (Lacombe, 2017) in Figure 5.6.

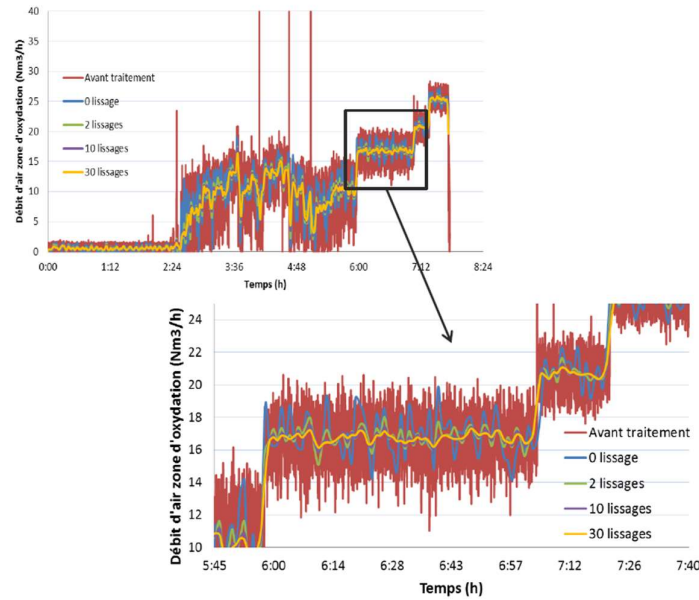


Figure 5.6 - Comparison of the Smoothing effect for various Smoothing Numbers. (Lacombe, 2017)

- Loss of input variables in case of program error

Should there be an error in the program, for whatever reason, the input variables would instantly be lost. This often meant that, unless the user went back and reintroduced them into the program, the program would be unable to proceed and would very often crash.

- Inability to press the cancel button

As the program only used basic Input Boxes and Message Boxes, the cancel button could very rarely be pressed without causing errors and, alas, crashing the program, forcing the user to restart the whole process.

- Selection of time intervals to be deleted much too morose

In the Deletion module, the flagged intervals were presented to the user one-by-one. The user would then select whether or not to delete them. As there could often be many such intervals, to do so on a one-by-one basis was immensely time consuming and fastidious.

- Aesthetically unpleasant presentation of Start page

Though the buttons were numbered, the order in which the program had to be executed was not immediately clear. For example, the user could jump straight from Button 5 (Simplification) to Button 8 (Deletion of time intervals) with no issues whatsoever. Such a thing was not possible from Button 4 (Creation of Raw Data Sheet) to Button 5.

The .csv kept their names exactly as they were prior to extraction - in other words, they had “.csv” written on them. This meant that most Worksheets had a name like “FT5000.csv” which was aesthetically unpleasant and unnecessary.

The order of the pages was also a bit senseless. The Raw Data Sheet (and derivatives) being the most important, they were nevertheless sent to the last positions. This meant

that if the user wished to consult them, he would have to manually search them through tens of Worksheets. This was unnecessarily time-consuming.

- Time-consuming navigation between Worksheets

There was no way to “fast-travel” between Worksheets. What that meant was that, if the user wished to inspect a specific Sheet, he would have to navigate through all the tens of Worksheets in search of it. And then do the process in reverse to return to the Start page.

- Occasional bugs

These were small and hard to detect but could occasionally have large consequences. One such bug, for example, led the program to not register around 80% of the smoothed values for a specific sensor in the Raw Data Sheet. They had to be searched and corrected but, seeing as they were small, they will not be referred.

5.4 Ameliorations and comparison with previous version

5.4.1 Smoothing by Array

In the previous version of the program each averaging step made during the smoothing process was written in an adjacent Excel column - in other words, a new column containing the newly averaged values was created (to the right of the previous one) and filled with the newly-averaged values. This would mean that, for high Smoothing Numbers, the program would take an enormous amount of time to complete the process.

The solution for this issue was to do the entirety of the averaging cycles using virtual arrays and only write the results at the very last iteration. To expand on this, two virtual arrays (dimensioned in accordance with the value-column they aimed to treat) are created for each raw Worksheet. These are called the Anterior and Posterior arrays. At the start of the process, the Anterior Array copies the data directly from the Excel columns. The values from this array are the ones subjected to the averaging - the results are then registered into the Posterior array. At the end of a cycle, the Anterior array copies the values from the Posterior Array and redoes the whole cycle. Once this is finished, the values are written into the Excel table (Figure 5.7).

The difference was impressive. The program was run using a Smoothing Number of 10 and, in the previous version, took around 13 minutes to complete the smoothing process. By comparison, in the new version it took 1 minute and a half, approximately. Another advantage of this method was that the Smoothing Number now has a much smaller influence in the time the program takes to run the smoothing process - this is because the calculations, as long as they are done virtually, are very fast, with the writing of the results taking up a much larger slice of time.

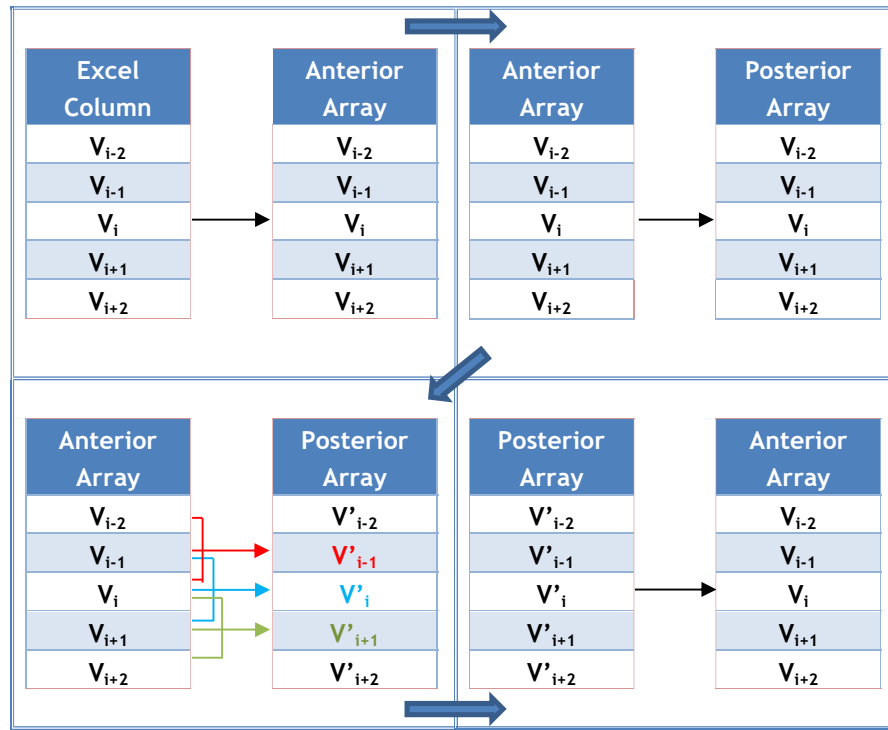


Figure 5.7 - Graphical display of the Smoothing Process using only virtual arrays. Here the Period is 3.

5.4.2 Introduction of new Smoothing parameters

Even when using very high Smoothing Numbers, the effect of using the Two-Point Moving Average Trendline function was not satisfactorily emulated. Also, the use of very high Smoothing Numbers substantially increased the amount of time the program took to complete the smoothing (though this issue was mitigated by using virtual arrays). This led to the introduction of two new parameters: The Period (P) and the Maximum Deviation (σ). The Period simply indicates the number of rows (or values) which are taken into account in each averaging. As for the Maximum Deviation, it indicates a maximum percentual amount of deviation a certain value can have from the mean value of the averaged interval (Equation 5.3).

$$\frac{V_i - Avg}{Avg} \cdot 100\% \leq \sigma \quad (5.3)$$

5.4.3 User-Friendly Changes

Various changes were also done to the interface.

- Redesign of Start sheet

To make the program more intuitive to the user, the use of a numbering system for the buttons was abolished and replaced with unlockable boxes. These boxes separate the various stages of the program and will only be unlocked once all the preconditional processes have been run. A circuit of arrows also aids the user to understand the logical sequence of processes.

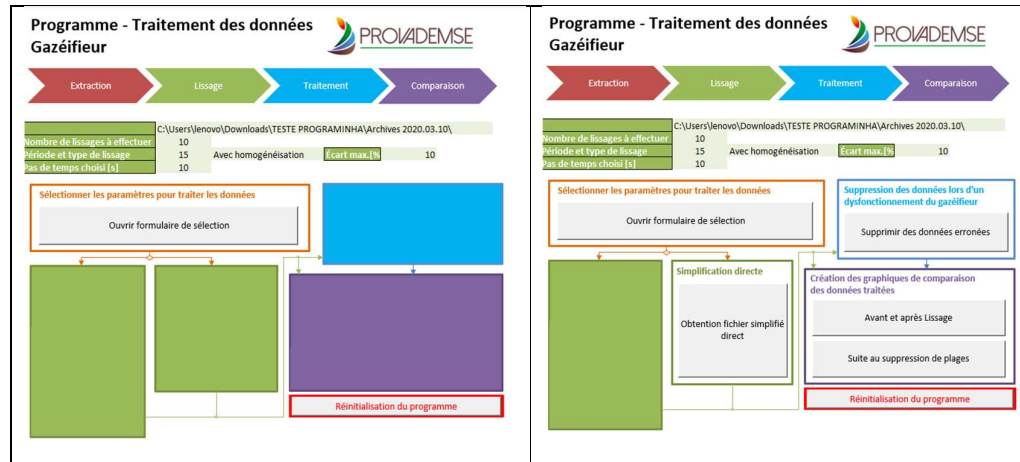


Figure 5.8 - New user interface. The boxes are unlocked by clicking the buttons in sequential order (left to right).

This not only allows for a more intuitive use of the program, it also prevents the user from accidentally crashing it by calling a Macro which still lacks the requisite information to run. It also gives the program a more polished appearance.

Button 7 was discarded as it served no real purpose besides, perhaps, preventing the program from crashing due to the loss of the inputted variables. To solve this last problem, a table was created in the very Start worksheet which stores these variables (Figure 5.8) - they can be retrieved from here by the program at any point, preventing the aforementioned crashes. Additionally, it reminds the user of what values were inputted.

- Introduction of fast-travel options

A new permanent sheet - that is, a sheet which is not erased once the program is restarted - was introduced: the Index. This Index is self-actualising, meaning that it will always display the Worksheets present in the Workbook, whatever the stage of the program the user is at (Figure 5.9). This is done by a code, inserted into the Worksheet itself, which causes the list to self-actualise whenever the Worksheet is opened. All of the Worksheet names have hyperlinks which will lead the user directly to them upon clicking. This is tremendously convenient and saves the user a lot of work and time.

Index de feuilles	Index de feuilles
# Nom de feuille	# Nom de feuille
1 Start	1 Start
	2 Données brutes
	3 AT0800
	4 FT4010
	5 FT4020
	6 FT4030
	7 FT5000
	8 FT6000
	9 FT7000
	10 FT8010
	11 NbCycleAlimBio0
	12 NbCycleDecendrage0
	13 PT0500
	14 PT0510

Figure 5.9 - Self-actualising Index sheet. It will self-actualise every time it is opened.

One can also see that the “.csv” was removed from the Worksheets’ names. It gives the Excel file a much cleaner look. A few more subtle changes were also made. Firstly, the Raw Data Sheet (and derivatives) are now stored right next to the Start and Index sheets.

Secondly: before, when the user created new Worksheets - be it by pressing Button 3 (Smoothing) or Button 4 - the program remained in the last active Worksheet. In other words, the user would be left with the last Worksheet open, generally at the rightmost position, having to traverse back “manually” to the Start. This was changed: the program now automatically returns to the Start Worksheet at the end of each process (except for the graph creating ones).

To allow for a quicker return to the Start sheet, a Button was added into the Excel ribbon. By pressing it, the user instantly returns to this Worksheet (Figure 5.10). However, it must be said that this button must be recreated every time the program changes computers or location.

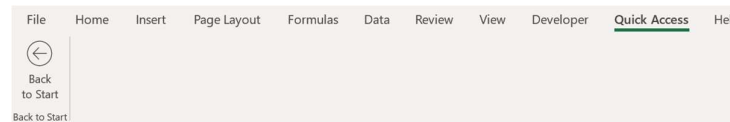


Figure 5.10 - Fast-travel button added into Ribbon. This button calls forth a Macro which opens the Start Worksheet.

- Creation of more compact, faster and informative User Forms.

Many issues were present as pertains to the user inputs. The methods for doing so were exclusively simple Input Boxes or Message Boxes. This presented not just the problem that pressing “Cancel” would often crash the program (by returning a vbNull variable which the code did not recognise) but also issues of practicability. For example, the location of the folder, Smoothing Number and Time Interval variables would be introduced one at a time, in separate Input Boxes.

These issues were solved by creating User Forms for each process. So, to return to the previous example, now all of those variables are introduced in the same User Form (“Parameter Insertion”) (Figure 5.11) and then stored in the Start sheet table. It is now possible to press the “Cancel” button without causing any errors - though this will erase the information already present in the Start sheet table. If the user wishes to simply keep the parameters as they are already registered, he may simply press “Skip” and keep them. This makes for a much simpler and intuitive method.

 The image shows a Windows-style dialog box titled 'Insertion de paramètres'. It contains several input fields and buttons. At the top, there is a button labeled 'Sélectionner le dossier' and a small 'Aide' button. Below this is a text input field. Then, there is a label 'Introduire nombre de lissage à effectuer' followed by a numeric input field. Below that is a label 'Choisir période de lissage' followed by a dropdown menu. Then, there is a label 'Introduire intervalle de temps pour la simplification' followed by a numeric input field. At the bottom, there are three buttons: 'Enregistrer', 'Sauter', and 'Cancel'.

Figure 5.11 - Parameter Insertion User Form. This Form allows the user to input all the parameters and once, or even to skip it and leave them as they are.

It was thought that there was no genuine need to separate the processes of Extraction, Smoothing, Creation of Raw Data Sheet and Simplification. They would, after all, necessarily be called upon in a row. Therefore, it would be useful to have a Button which

would perform all said functions at once, needing no further user input⁸. This then created a difficulty, however. If any error was detected, or a Worksheet was deleted for having no data requiring processing, the program would be stopped until the user acknowledged it. This defeated the purpose of automating the whole process. Also, there was no way of knowing how far along the 4 processes the program was. To solve this, a User Form, or Wait Box, was created. This box contains, on the upper left side, 4 checkboxes which inform the user as to which processes have been concluded; which process is ongoing is written on the Text Box to its right; below there is a Text Box which registers which Worksheets were deleted in the intervening processes (Figure 5.12).

Figure 5.12 - Data-Processing module Wait Box. It provides the user with information about which processes are being executed.

Another large issue related to Input Boxes was the Deletion process. As mentioned, every time an interval was flagged, the user was asked whether or not to delete it. This could be extremely morose (for example, during one trial-run, 200 such intervals were identified). As an added complication, once the process was launched it could not be interrupted as pressing Cancel would cause the program to crash. The solution for this was to create a List Box storing all the flagged time intervals. From there, the user simply has to check the intervals he wishes to erase. This saves an enormous amount of time and effort, besides looking much more pleasing to the eye (Figure 5.13).

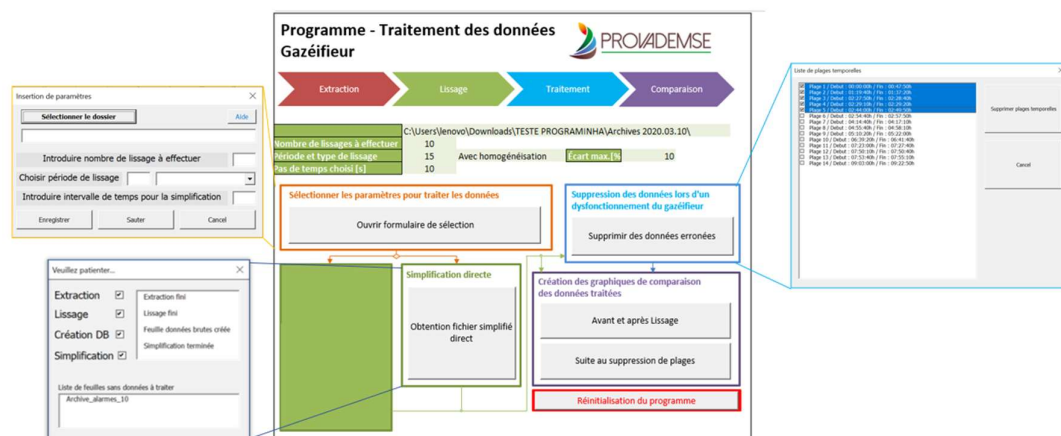


Figure 5.13 - Input User Forms added into the program, displayed connected to the buttons which call them forth.

⁸ The possibility to do these processes step-by-step was kept as there might be some use in inspecting the Worksheets halfway through the processes. The user will choose to either do it all-at-once or step-by-step, the alternative path becoming blocked after the choice has been made (Figure 5.13).

5.4.4 Influence of the different parameters in the Smoothing process

Despite the introduction of several parameters into the Smoothing, the effect, or “weight”, that each one has on the averaging, was unknown. A comparative study was then carried out. One of the three values (Smoothing Number, Period or Maximum Deviation) was kept constant and the other varied. However, prior to this a preliminary study was carried out to determine which sensor data displayed the most sensibility to the smoothing process (Table 5.2) - that is to say, whose data curves showed the most evident changes after being smoothed⁹. After analysing the effect of the Smoothing Process on various sensor values, it was decided that its effects were clearest on the FT500 and FT600 datasheets. As such, they are the ones which will be displayed for this comparative study (Table 5.3 to Table 5.7).

Table 5.2 - Sensitivity of each sensors' data to the Smoothing Process.

Sensibility	High	Medium	Low				
%O ₂			X	Temperature			X
AT080			X	TT050			X
Flowrate	X			TT051			X
FT401	X			TT052			X
FT402	X			TT053			X
FT403	X			TT054			X
FT500	X			TT400			X
FT600	X			TT500			X
FT700	X			TT501			X
FT801			X	TT600		X	
Pressure		X		TT601			X
PT050		X		TT800		X	
PT051			X	TT801			X
PT500		X		TT900			X
PT501	X			Speed		X	
PT900	X			VK500		X	
Weight		X		VK600	X		
WT010		X		VK700		X	

⁹ It is supposed that this sensibility will be directly linked to the existence, or lack thereof, of significant or acute variation over small timesteps in the values registered by the sensors.

The system of classification in Table 5.2 means, *grosso modo*:

- High: The curve is difficult to interpret or read before the smoothing and is rendered totally understandable by the process.
- Medium: The smoothing has not had much of an effect, either because the curve trend was already somewhat comprehensible or because the impact was not that significant, though it has been noticeable.
- Low: Either the curve trend was already perfectly clear, or the smoothing has done little-to-no difference.

By regarding Table 5.2 one concludes that the smoothing process will exert very little effect for most of the temperature sensors or the Lambda probe. In fact, by looking at the curves obtained from the raw data from these sensors it is noticeable that their curve trends are already perfectly understandable. One supposes that this must be so due to the slight variations in the temperature or oxygen concentration values. This is further reinforced by noting that the temperatures at the heat exchangers are more sensitive to the smoothing process - presumably because they are exposed to the much higher syngas' temperature variations.

The flowrate sensors stand in complete contrast. Given their violent variations, the curves are completely indecipherable if not subjected to a rigorous smoothing process. It must be said, though, that the water-cooling circuit is an exception to this, due to having a stable flowrate.

It is by examining the pressure sensors that one finds the most interesting information. The pressure sensors close to the boiler suffer very violent variations - understandably so, given their utter dependence on the syngas flowrate, itself prone to considerable instability. Within the gasification reactor, the rate of fluctuation is not as significant, though it does exist. An exception is in the entry zone - here there is very little fluctuation.

As for the remaining sensors, it is understandable that VK600 (air heat exchanger) is the one prone to highest variations, as it also depends on the syngas flowrate, temperature and pressure for its calibration. The remaining speed sensors do not register such instability, but, as would be expected, they are not extremely stable either. The fluctuations in the weight sensor are, one supposes, due to vibrations of the platform where the sensors are located.

Now possessed of this information, a comparative study of the effect of each Smoothing parameter is carried out. The results are displayed from Table 5.3 to 5.8.

In Figures 5.14 and 5.15 the Maximum Deviation was not used at all.

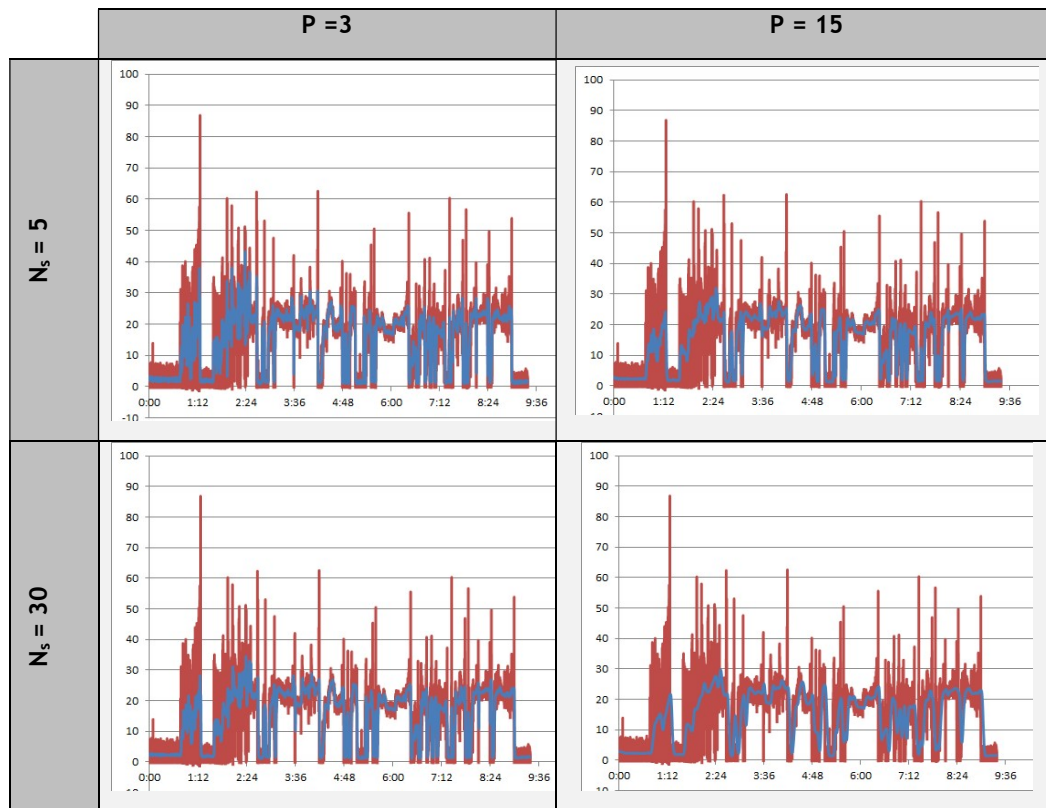


Figure 5.14 - Effect of the variation of N_s and P on the Smoothing Process (FT500).

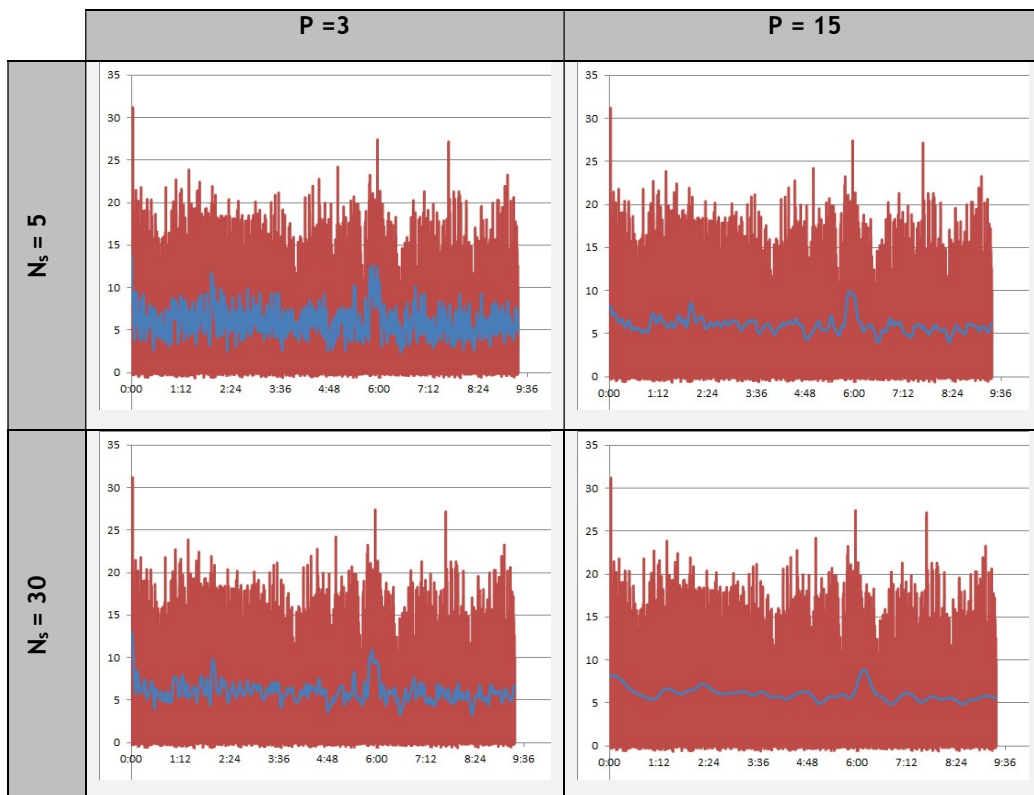


Figure 5.15 - Effect of the variation of N_s and P on the Smoothing Process (FT600).

In Figures 5.16 and 5.17 the Smoothing Number was kept at 10.

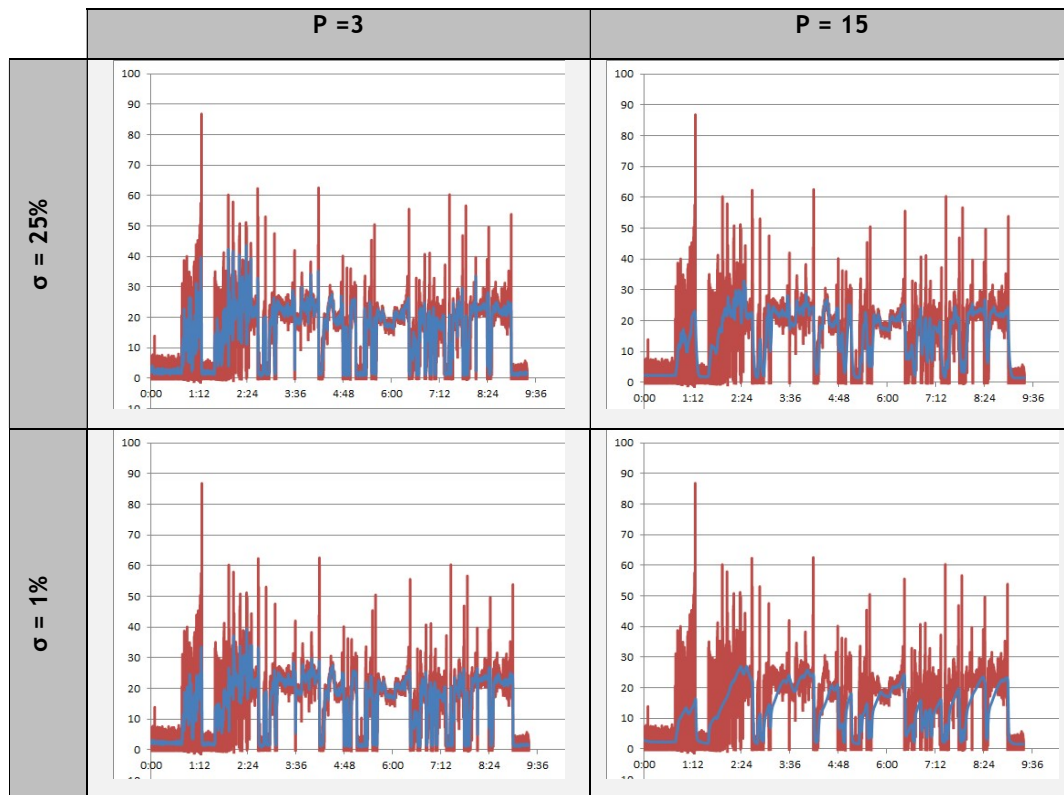


Figure 5.16 - Effect of the variation of the σ and P in the Smoothing Process (FT500).

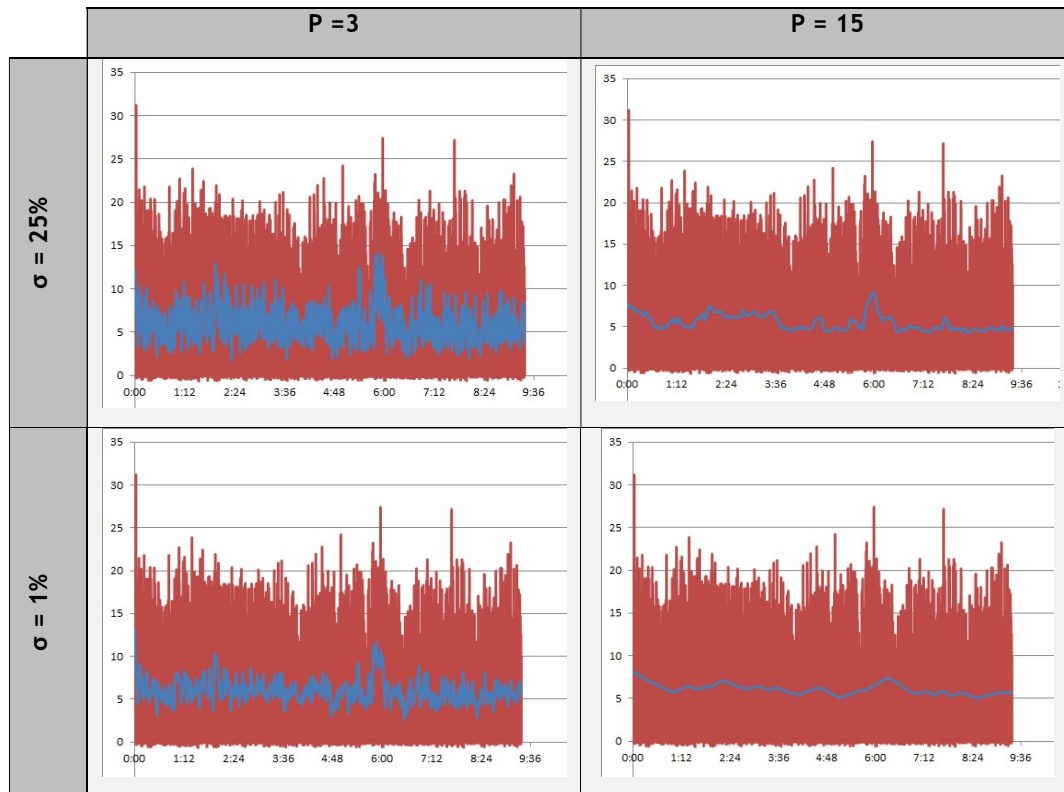


Figure 5.17 - Effect of the variation of the σ and P in the Smoothing Process (FT600).

Finally, in Figures 5.18 and 5.19 the Period was kept at 7

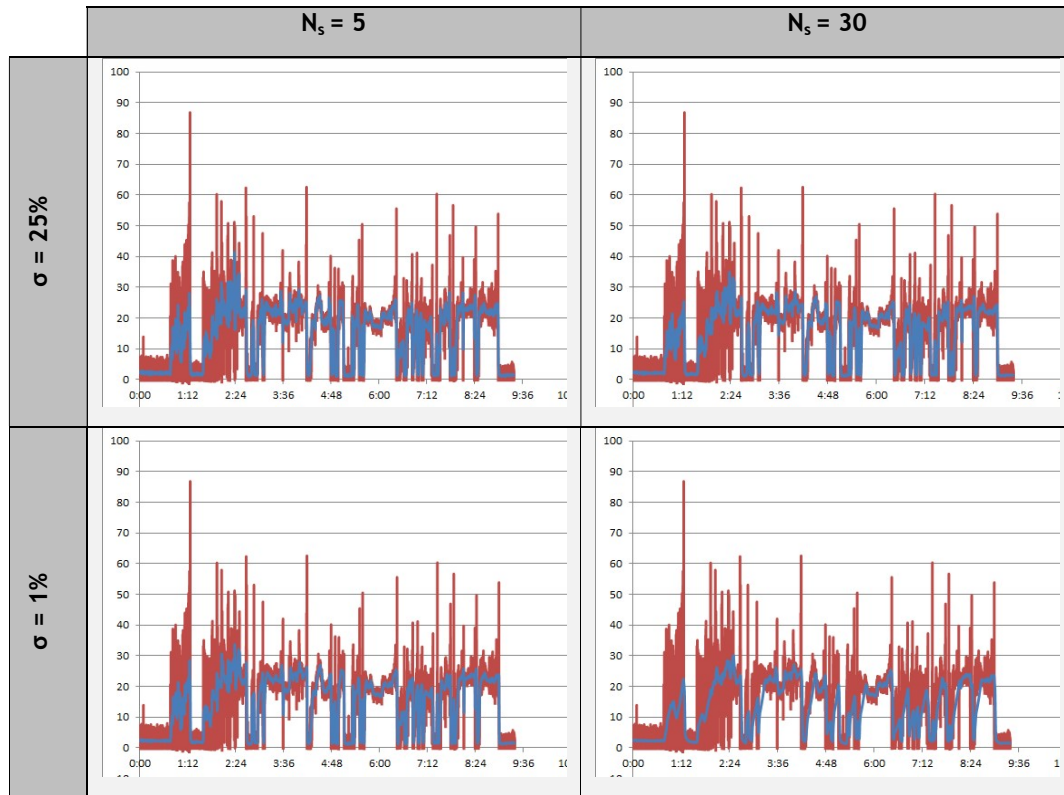


Figure 5.18 - Effect of the variation of σ and N_s in the Smoothing Process (FT500).

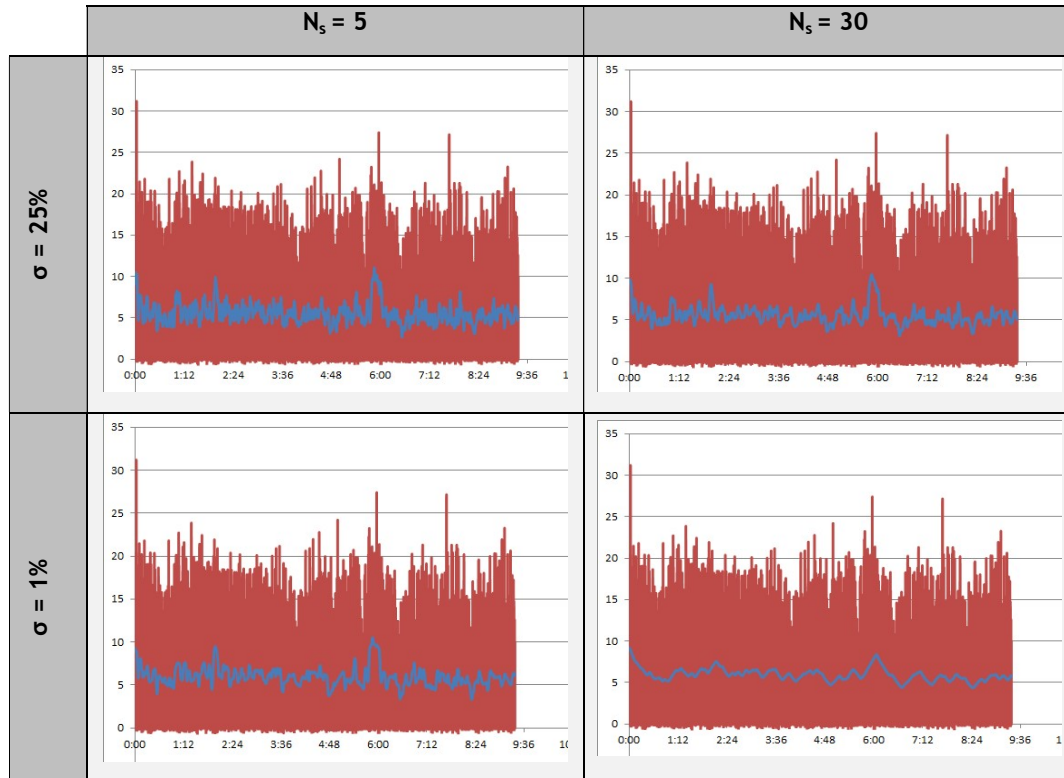


Figure 5.19 - Effect of the variation of σ and N_s in the Smoothing Process (FT600).

Results and Comparison

Unless extreme values are used, it becomes clear that the Maximum Deviation is not an especially useful parameter to use. Its effect is, in a way, to produce a smaller smoothing within the smoothing. Putting it in clearer terms, the Maximum Deviation will smooth the peaks contained within the averaging intervals. Nevertheless, its general effect is not strongly felt. In fact, its usefulness will run out quickly in relation to the Smoothing Number as after a few cycles it will produce no effect whatsoever. It makes itself more clearly felt for higher Period numbers, however. In fact, if used carelessly with high Periods it will corrupt the curve trend to the point of uselessness. Looking at the curves where it was used, it can be seen that they present smoother “peaks”, but this can only be glimpsed at values lower than around 15%. It can also be seen that if very low Maximum Deviation values are used it will generally completely derail the smoothing process. Therefore, if it must be used, values no lower than 5% are advised. Still, these are very general guidelines and depend on the other two parameters.

Though the Smoothing Number is the most fundamental parameter (after all, it must be at least higher than 0 for there to be any smoothing at all) its overall effect is strongly influenced by the Period. When the Period is low, even huge Smoothing Numbers will have a limited effect, whereas if the Period is very high even small Smoothing Numbers will quickly distort the curve trend. The Smoothing Number, of all parameters, is the one which has the most influence as far as program weight is concerned - which essentially means that it should always be as low as possible. Even for low Periods, little difference is felt after a N_s of 10, and once a number approaching 30 has been hit, the difference is unnoticeable.

The Period, interestingly, despite its status as an “auxiliary” parameter, is the one whose variation is felt the most strongly. When it is low, both the Smoothing Number and the Maximum Deviation become very limited in their effect, but when it is high the other two must forcibly be small so as to prevent the trendline from becoming distorted. This is made very evident by looking at the tables where the Period was kept constant: the variations are much smaller between the curves. From the trials ran, it was determined that Periods superior to 20 are strongly unadvised. Somewhere between 7 and 15 appears to be ideal, if combined with a Smoothing Number of 5 to 10.

5.4.5 Future Developments

Regardless of the achievements in load reduction, and speed-increase, the program remains very heavy on certain steps, especially the Simplification and Deletion stages. This is because it copies and rewrites a huge quantity of cells, the most morose process for Excel. Future improvements should focus on minimising the weight of these steps.

Regarding the deletion of undesired time intervals, the question was posed as to whether or not it would be better to employ it before having the data undergo the smoothing. There is a risk this will distort the obtained data, due to having the program average values which occurred with a large time separation between them. However, it would present much greater precision for the deletion - abnormalities would be easier to detect (and erase) and this could result in cleaner curves. This is another area of possible development.

It must also be mentioned that there is room for improvement in the domain of User Forms, as there may remain occasional bugs which cause crashes.

Chapter 6 Results-analysis Program

Once the data collected from the sensors has been processed, it must be analysed - that is to say, calculations must be extrapolated from it so as to evaluate the quality of the syngas, of the fuel and of the trial. The assigned task here was a similar one: to develop a VBA-derived program which would achieve this objective more easily, more quickly, more intuitively and less clumsily.

Though procedures for this analysis were already in place, one of the desired outcomes of developing this program would be the stripping away of unnecessary procedures - only the bare minimum required for the calculations would be kept. The program should be as lean and simple as possible.

This chapter will follow a dissimilar structure from the last one. It will begin by displaying what outputs are wanted from the program and will then explain all its intermediate calculations and required inputs. At the end, possible routes of improvement will be discussed.

6.1 Desired Output

There are two fundamental types of output wanted from this program: the Mass and Energy Balance Sheet and the Comparison Graphs. Both will now be explored.

6.1.1 Mass and Energy Balance Sheet

At the very end of the program's running, the following Balance Sheet (Figure 6.1) must be properly filled:

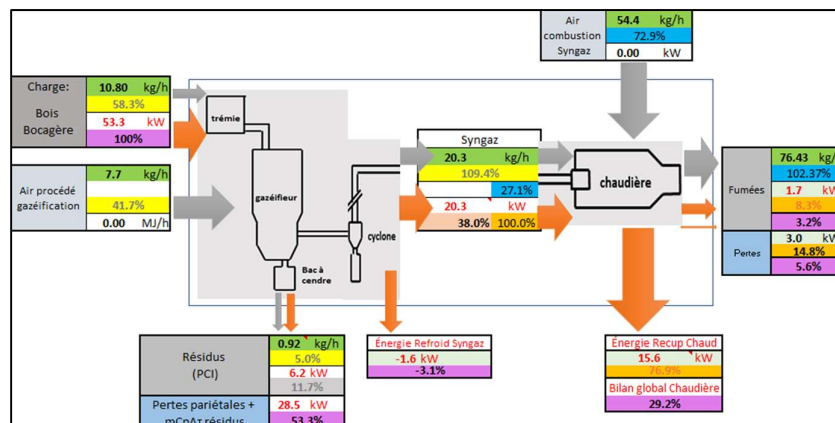


Figure 6.1 - Example of a filled Mass and Energy Balance Sheet - this is the main desired output from this program.

It should be mentioned that some of these parameters, specifically the ones pertaining to the fuel and the residues, must be registered as the results of experiments not encompassed by this dissertation. They may be directly written into a table in the program, but the methods by which they are acquired will be ignored.

The final results of the various calculations (the “Mass and Energy Balance”) are often grouped in a summary table, which the program must create. It selects data only from the time interval wherein a stable regime was achieved (said interval must be inputted by the user). This table must contain:

Sum total of:

- Air injected into the gasifier (Nm^3/h)
- Syngas flowrate (Nm^3/h)
- Extraction fan air flowrate (Nm^3/h)
- Air injected into the boiler (Nm^3/h)
- Fumes flowrate, both theoretical and measured (Nm^3/h)
- Syngas power (kW)
- Syngas theoretical power (kW)
- Fumes measured power (kW)

From these the sum total of corresponding volumes, mass and energy are extracted, using a multiplication by the time-step used in the Raw Data Sheet.

Average:

- Air flowrate into the pyrolysis zone (Nm^3/h)
- Air flowrate into the partial oxidation zone (Nm^3/h)
- Air flowrate into the reduction zone (Nm^3/h)
- Syngas flowrate (Nm^3/h)
- Heat exchanger air flowrate (Nm^3/h)
- Boiler injected air flowrate (Nm^3/h)
- Water flowrate (L/min)
- Fumes flowrate - theoretical, measured at the boiler outlet and emitted into atmosphere (Nm^3/h)
- Oxygen concentration in fumes at boiler outlet (%)
- Syngas power (kW)
- Syngas power discounting fumes' power (kW)
- Power transferred from syngas to heat exchanger (kW)
- Power received by air in the heat exchanger (kW)
- Theoretical syngas power (kW)

Following an analogous procedure to the sum total, the time-step is used to calculate the corresponding average mass flowrates and energies.

It may be observed that some of these values can be directly lifted from the Raw Data Sheet (e.g. the average air flowrate into the pyrolysis zone, given by FT052). Nevertheless, many will require a series of intermediate calculations, which this program will do, and which will be explained in sub-chapter 6.2.

6.1.2 Comparison Graphs

The program should also be able to create a series of graphs allowing the operator to visualise the results from the trial. These graphs are:

- Air injected into the gasifier (FT051, FT052, FT053);
- Head loss in the gasifier (PT050, PT051);
- Evolution of the reactor temperatures (TT050, TT051, TT052, TT053, TT054)
- Temperature change in the syngas line and heat exchanger air (TT500, TT510, TT600, TT601);
- Flowrates throughout the syngas line (FT500, Fumes Flowrate, FT700);
- Temperature changes in the water leaving the boiler (TT800 TT801, TT900);
- Comparison of Heats: syngas theoretical power, fumes power, syngas power without fumes and measured syngas power.

These graphs are particularly important as they allow the engineer to visualise the behaviour of vital trial components. The reasons why they are of interest will now be explained.

Flowrate of air injected into the gasifier

When it comes to controlling the trial's quality this is likely to be the most significant parameter. It has a direct and strong impact on the conversion of solid matter, the temperature levels within the reactor, the quantity and quality of the produced syngas and the global power balance.

Temperatures within the reactor

It is worth mentioning that these temperatures are not, in fact, those of the reactions themselves. This is so due to the thermocouples being placed on the reactor's inner walls to avoid interfering with the fuel flow. This being the case, it stands to reason that the reaction temperatures will be substantially higher. This difference in temperature, though ignored here, can be of great significance (Tagutchou, 2008).

As would be expected, the temperature does not display the same behaviour in the different zones of the gasification reactor.

At the top of the reactor the temperature does not usually surpass 85°C. Indeed, it generally operates in a range from 60 to 80°C - this area's temperature is maintained in this range by the automatic addition of solid fuel if said limit is approached.

The wall next to the oxidation zone has much more wildly varying temperatures -this is, after all, where the most volatile reactions occur. In fact, though the temperatures registered at the syngas annular zone (TT040) are normally higher, this is simply due to the already mentioned fact that the thermocouple measures the wall's temperature at the oxidation zone. This deviation from reality is not as strongly felt in the annular zone as it lacks a strong transversal temperature gradient due to the components being in gaseous phase.

Head loss within the reactor

The rotation speed of the syngas extraction fan is defined by the pressure at the top of the gasifier. The speed increases with a decrease in pressure. The latter has a limit of 200 Pa (relative pressure). It is, therefore, important to see the evolution of this parameter.

The head loss is obtained from the difference between the pressure at the top of the gasifier and at the reduction zone. This head loss can have rather large values - though the pressure at

the top tends to be stable, the reduction area's pressure can vary a lot. This head loss should not be much superior to 3000 Pa.

The head loss is often owed to the granulometry of the solid fuel, the effects of clogging and bad hydrodynamic circulation of solid matter. The type of fuel entering the machine will also exert an effect, as longer or less dense solid matter will not flow as easily. Occasionally, very sudden pressure drops will be registered - these are commonly due to gas that, having become trapped by agglomerations of solid matter, builds up pressure until it explodes outwards (this phenomenon presents no danger to the integrity of the machine or its users).

Temperatures along the syngas' line

Here the evolution of the temperatures of the syngas and the cooling air from the heat exchanger will be compared. The heat exchanger uses the forced convection of air to cool the syngas, though it will be natural convection in case of fan malfunction. This air is occasionally heated to high temperatures, which might constitute a source of reusable heat.

Flowrate of syngas, boiler combustion air and fumes

The syngas and air have a dependent relationship within the boiler. This is established by stoichiometry. If less syngas is entering the boiler, then higher amounts of air will be injected into it. There is no flowrate sensor for the fumes so this outlet flowrate must be calculated from theoretical equations which will be explored later in this chapter.

Recovered Boiler heat

The energy from the combustion in the boiler is used to heat water - the temperature difference measured in this fluid allows one to estimate how much power has been recovered from the syngas combustion.

Comparative Heats

This graph displays and compares the syngas power obtained from the trial (with and without counting the fumes' power, also represented) with the theoretical syngas power. The difference between them, owed to imperfections in power conversion, permits the engineer to estimate the quality of the trial.

6.2 Theoretical equations

This program will, in essence, have encoded into it the equations which return the values sought after by the engineers. So, evidently, the first step in its conception is to enumerate what such values are and what equations conduce to them.

Though many of the intermediate calculations can be obtained by simple mathematical operations making use of the processed sensor data, others require using significantly more complex equations. Therefore, these theoretical equations will now be explained.

6.2.1 Boiler

To calculate various fundamental Heats, quite a bit of data must be extracted from the boiler. First, we list the chemical reactions happening within the boiler (Ruje, 2016), represented in Equations 6.1 to 6.5:



From here, a mass flowrate balance (Figure 6.2) can also be made (Equation 6.6):



Figure 6.2 - Components entering and exiting the boiler.

$$\dot{m}_{AirExtractor} + \dot{m}_{CombAir} + \dot{m}_{Syngas} + \dot{m}_{Propane} = \dot{m}_{Fumes} \quad (6.6)$$

From which follows:

$$Q_{AirExtractor} \cdot \rho_{Air} + Q_{CombAir} \cdot \rho_{Air} + Q_{Syngas} \cdot \rho_{Syngas} + Q_{Propane} \cdot \rho_{Propane} = Q_{Fumes} \cdot \rho_{Fumes} \quad (6.7)$$

The amount of oxygen entering and leaving the boiler must also be constant, which means:

$$Q_{molO_2, CombAir} + Q_{molO_2, AirExtractor} + Q_{molO_2, Syngas} = Q_{molO_2, Fumes} + Q_{molO_2, stoich} \quad (6.8)$$

By again referring to the chemical reactions taking place within the boiler, one can state:

$$Q_{molO_2, stoi} = \frac{1}{2} Q_{mol, H_2} + \frac{1}{2} Q_{mol, CO} + 2Q_{mol, CH_4} + 5Q_{mol, C_3H_8, syngas} + \frac{3}{2} Q_{mol, H_2S} + 5Q_{mol, C_3H_8} \quad (6.9)$$

And, therefore, the theoretical oxygen flowrate into the boiler is:

$$Q_{O_2 CombAir, t} = \frac{Q_{molO_2, stoich}}{v_{molar}} \quad (6.10)$$

And the theoretical Air Flowrate into the Boiler can now be established:

$$Q_{Air Comb, t} = \frac{Q_{O_2 CombAir, t}}{\%O_{2, Air}} \quad (6.11)$$

A similar logic applies to the oxygen's flowrate in the measured air flowrate:

$$Q_{O_2 CombAir, r} = Q_{Air Comb, t} \cdot \%O_{2, Air} \quad (6.12)$$

By rearranging Equation 6.7, one can establish the theoretical Fumes flowrate:

$$Q_{Fumes, t} = \frac{Q_{AirExtractor} \cdot \rho_{Air} + Q_{CombAir} \cdot \rho_{Air} + Q_{Syngas} \cdot \rho_{Syngas} + Q_{Propane} \cdot \rho_{Propane}}{\rho_{Fumes}} \quad (6.13)$$

These demand the prior establishment of the Air Flowrate in the Fumes Extraction Fan. To extract the fumes from the boiler the Extraction Fan injects a certain amount of air into the mixture. This air volume must be calculated. By combining equations 6.8 and 6.12, one concludes that:

$$Q_{AirExtractor} = \frac{Q_{O_2, stoich} + A - Q_{CombAir} \cdot \%O_{2,Air} - Q_{Syngas} \cdot \%O_{2,Syngas}}{\%O_{2,Air} - \frac{\rho_{Air}}{\rho_{Fumes}} \%O_{2,Fumes}} \quad (6.14)$$

$$A = \frac{\%O_{2,Fumes}}{\rho_{Fumes}} \cdot (Q_{AirComb} \cdot \rho_{Air} + Q_{Syngas} \cdot \rho_{Syngas} + Q_{Propane} \cdot \rho_{Propane})$$

6.2.2 Fumes Extraction

When calculating the fumes' flowrates, it is important to know how much air is added into the mixture by the Fumes Extraction Fan (Figure 6.3). This will permit the knowledge of the fumes' composition when they are released into the environment.



Figure 6.3 - Mixture expelled into the atmosphere.

The air added into the fumes by the extraction fan will be mostly constant through every trial - in other words, it needs only be calculated once. This was done by measuring both the fumes flowrate and oxygen concentration in the fumes exiting the boiler and those exiting the chimney.

The sum total of the oxygen's mass is given by Equation 6.15:

$$Q_{Fumes} \cdot \%O_{2,Fumes} + Q_{AirExtFumes} \cdot \%O_{2,Air} = Q_{FumesChimney} \cdot \%O_{2,FumesChimney} \quad (6.15)$$

Which can be rearranged into Equation 6.16:

$$Q_{AirExtFumes} = Q_{Fumes} \cdot \frac{\%O_{2,FumesChimney} - \%O_{2,Fumes}}{\%O_{2,Air} - \%O_{2,FumesChimney}} \quad (6.16)$$

The measured values were the ones presented in Table 6.1:

Table 6.1 - Oxygen concentration measured at the boiler outlet and exiting through the chimney, as well as the theoretical concentration in air.

Fumes (Nm ³ /h)	155.00
%O _{2,Fumes} (AT080)	8%
%O _{2,Air}	21%
%O _{2,FumesChimney}	9.7%

By inserting the values into equation 6.16, one concludes what is in Equation 6.17:

$$Q_{AirExtFumes} = 24 \text{ Nm}^3/\text{h} \quad (6.17)$$

6.2.3 Heats

Once the flowrates have been established, the Heats can be calculated. We begin with calculating the theoretical syngas power through Equation 6.18:

$$P_{Syngas,t} = P_{LHV} + \dot{m}_{Syngas} \cdot Cp_{Syngas} (T_{Syngas} - T_{LHV}) \quad (6.18)$$

With T_{LHV} being the temperature at which the LHV of the syngas is provided (0°C) and the remaining values acquired from Equation 6.19 and 6.20:

$$\dot{m}_{Syngas} = Q_{Syngas} \cdot \rho_{Syng} \quad (6.19)$$

$$P_{LHV} = Q_{Syngas} \cdot LHV_{Syngas} \quad (6.20)$$

The syngas' LHV in its turn given by Equation 6.21:

$$LHV_{Syngas} = \%H_2 \cdot LHV_{H_2} + \%CH_4 \cdot LHV_{CH_4} + \%CO \cdot LHV_{CO} + \%H_2S \cdot LHV_{H_2S} \quad (6.21)$$

During the trials, part of this power is transmitted to the water circulating in the boiler and the remainder is dispersed in the fumes. Therefore, the real syngas power is estimated from Equation 6.22:

$$P_{Syngas} = \rho_{Water} \cdot Q_{Water} \cdot Cp_{Water} \cdot \Delta T_{Water} - Q_{Propane} \cdot LHV_{Propane} + P_{Fumes} \quad (6.22)$$

Attention must be made to the propane. Its presence can, occasionally, grotesquely affect the results if it is not carefully controlled due to its high LHV.

The fumes' power can be calculated once its flowrate has been calculated, through Equation 6.23:

$$P_{Fumes} = \rho_{Fumes} \cdot Q_{Fumes} \cdot Cp_{Fumes} \cdot (T_{Fumes} - T_{amb}) \quad (6.23)$$

Now that the theoretical equations to be utilised have been clearly established, a series of tables - heretofore referred to as Results Tables - will be provided, listing all of the intermediate calculations the program is supposed to perform.

6.3 Intermediate calculations

To obtain all of these results there are many intermediate results which are needed. They will be summed up in Tables 6.1 to 6.8. Some calculations require more complicated theoretical equations. These will be specified and, where necessary, explained.

6.3.1 Head Loss

Table 6.2 - Parameters calculated for the reactor Head Loss.

Head Loss			
Δp	Pa	Head loss in the gasification reactor	$PT051 - PT050$

6.3.2 Fuel Feeding

Table 6.3 - Parameters calculated for the fuel fed into the reactor. This particular parameter will be represented in a graph.

Fuel Feeding			
m	kg	Cumulative mass fed into the reactor	$WT010$

6.3.3 Hot Water

Table 6.4 - Parameters calculated for the water circling through the boiler. The fuel flowrate is obtained by plotting feed hopper mass variation versus time. The slope of the trend curve obtained from the graph in steady state is considered to be the flowrate of the fuel.

Hot Water			
ΔT_{Water}	$^{\circ}\text{C}$	Temperature gradient of water before and after cooling	$TT801 - TT800$
Q_{Water}	Nm^3/h	Water flow rate	$FT801$

6.3.4 Cooling Air

Table 6.5 - Parameters calculated for the air in the heat exchanger, used to cool the syngas upon extraction.

Cooling Air			
$\Delta T_{\text{CoolingAir}}$	$^{\circ}\text{C}$	Temperature gradient of air before and after cooling	$TT601 - TT600$
$Q_{\text{CoolingAir}}$	Nm^3/h	Cooling air flowrate	$FT600$

6.3.5 Syngas

The intermediate calculations for the syngas can be done directly from the Raw Data Sheet - except, that is, for the Heats. These will require more complex calculations. Furthermore, before they can be made, all other Results Tables must have been calculated. As such, this particular Results Table will be done in two separate parts, one encompassing the flowrates and the other the Heats.

Table 6.6 - Parameters calculated for the syngas obtained during the trial.

Syngas			
$T_{\text{Syngas}} - T_{\text{Amb}}$	$^{\circ}\text{C}$	Difference between syngas and room temperatures	$TT501 - T_{\text{Amb}}$
ΔT_{Syngas}	$^{\circ}\text{C}$	Temperature loss to the heat exchanger	$TT500 - TT501$
Q_{Syngas}	Nm^3/h	Experimental syngas flow rate	$FT500$
Q_{SyngasDB}	Nm^3/h	Dry-base syngas (not counting water)	$Q_{\text{Syngas}} / (1 - \%H_2O_{\text{Syngas}})$
$Q_{O_2, \text{SyngasDB}}$	Nm^3/h	Oxygen flowrate within dry-base syngas	$Q_{\text{SyngasDB}} \cdot \%O_{2, \text{Syngas}}$
Q_{molH_2}	kmol/h	Molar flowrate of hydrogen within syngas	$Q_{\text{Syngas}} \cdot \%H_{2, \text{Syngas}}$
Q_{molCH_4}	kmol/h	Molar flowrate of methane within syngas	$Q_{\text{Syngas}} \cdot \%CH_{4, \text{Syngas}}$
Q_{molCO}	kmol/h	Molar flowrate of carbon monoxide within syngas	$Q_{\text{Syngas}} \cdot \%CO_{\text{Syngas}}$
$Q_{\text{molC}_3\text{H}_8}$	kmol/h	Molar flowrate of propane within syngas	$Q_{\text{Syngas}} \cdot \%C_3H_{8, \text{Syngas}}$

$Q_{\text{molH}_2\text{S}}$	kmol/h	Molar flowrate of hydrogen sulfide within syngas	$Q_{\text{Syngas}} \cdot \% \text{H}_2\text{S}_{\text{Syngas}}$
$\dot{m}_{\text{Syngas}}$	kg/h	Syngas mass flowrate	Equation 6.19
$P_{\text{syngas,nofumes}}$	kW	Syngas power discounting fumes dispersion	$P_{\text{Syngas}} - P_{\text{Fumes}}$
P_{syngas}	kW	Syngas measured power	Equation 6.22
$P_{\text{theoretical}}$	kW	Theoretical syngas power (from PCI)	Equation 6.18
$P_{\text{syngas,echg}}$	kW	Syngas power transferred to heat exchanger	Equation 6.23
$P_{\text{syngas,airechg}}$	kW	Syngas power recovered by air-based heat exchanger	Equation 6.24
Error	%	Error between the two last lines	$\frac{P_{\text{syngas,echg}} - P_{\text{syngas,airechg}}}{P_{\text{syngas,echg}}}$

Equations 6.24 and 6.25 return the Heats exchanged in the heat exchanger during the syngas' exit from the reactor.

$$P_{\text{syngas,echg}} = Q_{\text{Syngas}} \cdot \rho_{\text{Syngas}} \cdot C_{p\text{Syngas}} \cdot \Delta T_{\text{Syng}} \quad (6.24)$$

$$P_{\text{syngas,airec}} = Q_{\text{Air}} \cdot \rho_{\text{Air}} \cdot C_{p\text{Air}} \cdot \Delta T_{\text{Air}} \quad (6.25)$$

6.3.6 Boiler Combustion Air

Although the air flowrate into the boiler has been directly measured by the FT700 sensor, most of the remaining calculations are theoretical.

Table 6.7 - Parameters calculated for the air flowrate within the boiler.

Boiler Combustion Air			
$Q_{\text{O}_2,\text{Stoich}}$	Nm^3/h	Oxygen flowrate in stoichiometric combustion	Equation 6.9
$Q_{\text{CombAir,t}}$	Nm^3/h	Theoretical boiler combustion air flowrate	Equation 6.11
$Q_{\text{CombAir,r}}$	Nm^3/h	Experimental boiler combustion air flowrate	FT700
$Q_{\text{O}_2\text{CombAir}}$	Nm^3/h	Oxygen flowrate within air	Equation 6.10

6.3.7 Fumes

Table 6.8 - Parameters calculated for the fumes exiting the boiler.

Fumes			
ΔT_{Fumes}	$^{\circ}\text{C}$	Temperature difference between fumes and ambient air	$T_{\text{T900}} - T_{\text{Amb}}$
$Q_{\text{Fumes,t}}$	Nm^3/h	Theoretical fumes flowrate	Equation 6.13
$Q_{\text{Fumes,r}}$	Nm^3/h	Experimental fumes flowrate	Equation 6.13
$Q_{\text{AmbFumes,r}}$	Nm^3/h	Ambient fumes flowrate	$Q_{\text{fumes,r}} + \text{Const.}$
$\% \text{O}_2$	%	Oxygen concentration in fumes	AT080

P_{Fumes}	kW	Power present in fumes	Equation 6.23
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6.3.8 Syngas Extraction Fan

Table 6.9 - Parameters calculated for the air flowrate from the syngas extraction fan.

Syngas Extraction Fan			
$Q_{\text{AirExtractor}}$	Nm^3/h	Air flowrate in extractor	Equation 6.14
$Q_{\text{O2Extractor}}$	Nm^3/h	Oxygen flowrate within air	$Q_{\text{AirExtractor}} \cdot \%O_{2,Air}$

As can be inferred from these tables, some Results Tables can be directly obtained from the treated data. However, some require significantly more sophisticated calculations (Fumes, Syngas, Boiler Combustion Air and Syngas Extraction Air) and will necessitate the introduction of further parameters into the program.

6.4 Required Inputs

Upon careful examination of the equations presented in sub-chapter 6.3, it may be ascertained that some additional parameters must necessarily be inputted by the user. These inputs may be required of the user in each run of the program or they may simply be grouped into the permanent tables. Whatever parameters are essential and must be introduced by the user in some form, are presented in Table 6.10.

Table 6.10 - Parameters which must be inputted into the program by the user.

Parameters	Components	Units
Specific heat (Cp)	Syngas, Air, Water, Vapour, Fumes	kJ/kgK
Density (ρ)	Syngas, Air, Water, Vapour, Propane, Fumes	kg/Nm^3
Low heating value (LHV)	Propane, Syngas	MJ/Nm^3
$\%V_{\text{inSyngas}}$	H ₂ , O ₂ , N ₂ , CH ₄ , CO, CO ₂ , C ₃ H ₈ , H ₂ S, H ₂ O	$kg/kmol$
Flowrate (Q)	Air Extractor, Propane	Nm^3/h

Special routines will be put in place for the Syngas' and Fumes' volume percent, as well as for the Propane flowrate (injected into the boiler).

6.5 Program Structure

This program will contain various Worksheets which must be filled prior to starting the calculations. Some of these inputs will be prompted by clicking specific buttons, whereas others must be "voluntary". Only once all of this preliminary information is present can the program begin the calculations and obtain the Results Tables. Figure 6.4 provides a graphic summary of the program's structure.

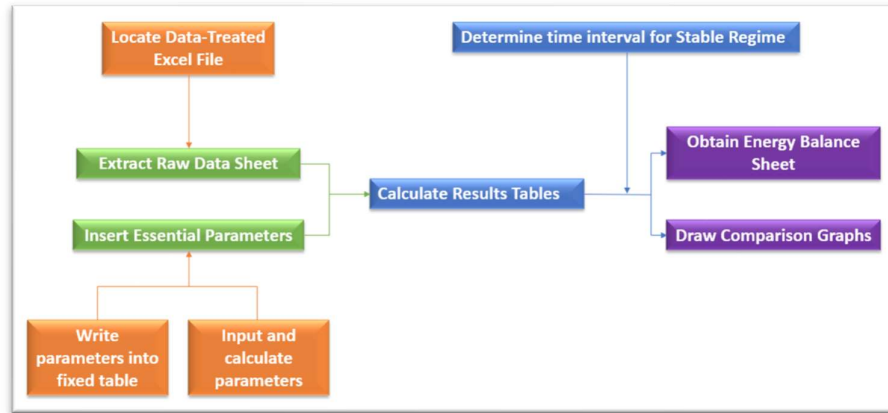


Figure 6.4 - Graphic depiction of the program's structure.

Like the Data-Treatment program, this program will also induce the proper operating sequence by a series of unlockable boxes in its interface. In addition, to inform the user as to which buttons have been clicked, the texts contained within will become coloured upon pressing. These are shown in Figure 6.5:

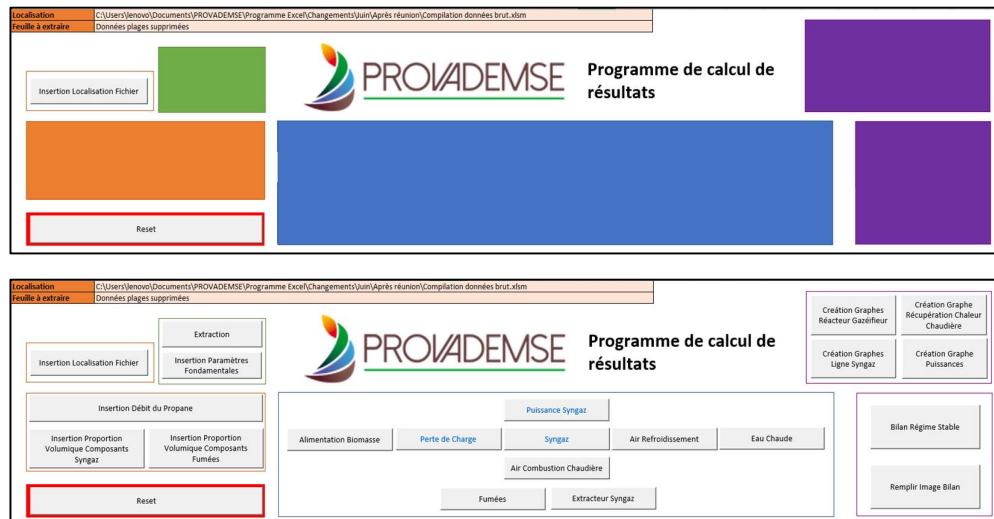


Figure 6.5 - User interface at Start Worksheet. This user interface also uses boxes which go from locked (above) to unlocked (below) as the program is run sequentially.

6.5.1 Permanent Worksheets

The main user interface, following the model set by the Data-Treatment Program, will be located at the first Worksheet, also named "Start". It will also contain a self-actualising Index for ease of navigation. This program will have built into it a series of Worksheets (their tabs being coloured orange or green) containing preliminary or complementary information about the gasification trial. These are:

- Trial General Data

This Worksheet contains general information about the trial, such as the type of fuel or its duration. The only fundamental information for the program's running to be extracted from it is the Ambient Temperature (in other words, it must be stored prior to starting the

calculations). The remaining information being either non-essential or to be filled in later by the program itself.

- Entry and exit data

In this Worksheets are two tables containing a series of values referring to entering components (Biofuel, Air and Propane) and exiting components (Solid Residues, Syngas, Fumes and Tar). Many of these have been measured in laboratory tests outside the scope of this work. Following a similar logic to the previous table, some of its data is absolutely essential (these cells are highlighted in yellow), others are non-essential, and some will be filled in by the program itself. In the following chapter the information contained in these two tables, where deemed relevant, will be provided.

- Treatment Tables

This Worksheets contains four kinds of tables. The orange tables contain information about the calculations and values to be acquired in the Results Tables (they are the same as the ones provided above). The green tables contain the molar mass, volume and mass percent of the syngas' and fumes' components. These are used to fill the blue tables, containing fundamental parameters of the syngas, the fumes and the injected propane, mainly the flowrates, density, LHV, specific heat and molar mass. The purple table contains a series of constants to be retrieved from the code in a later phase.

- Component Properties

This sheet contains a large table listing the molar mass, density, specific heat and LHV of the various chemical species present in a gasification trial. They too are retrieved by a Function in the VB code and stored for use in the calculations to follow.

6.5.2 Extraction

After filling or checking the orange Worksheets, the user must locate the Excel-file (the previous program) containing the already treated data by clicking the respective button. Once this is done, the user presses on "Extract". He must specify whether he wants to extract the Raw Data Sheet or the Deleted Time Intervals Data Sheet. Either way, it will be stored as a Worksheet named "Treated Data".

6.5.3 Insert Essential Parameters

This button must be pressed for the program to search and store the needed information from the permanent Worksheets. This is a necessary step for the calculations to be made entirely in the VBA code. Prior to executing this function, it will ask the user if he has verified that the tables have been properly filled. This button itself will only be unlocked once the user has inputted the volume percent of the syngas and fumes, as well as the averaged propane flowrate into the boiler. This is achieved by clicking the respective buttons, located in the orange box below.

The volume percent of the syngas' and fumes' components must be calculated based on averaged samples retrieved throughout the trial. For this the user must say how many samples were taken and indicate the observed proportion for each in the appropriate User Form, which will return an average for each. These averages will then be stored into the "Treatment Tables" Worksheet.

The propane flowrate is inputted directly into a User Form and stored in the Treatment Tables. Its other relevant parameters are automatically calculated.

Once the program has been fed all of these inputs, it will calculate and store all the necessary variables in the “Treatment Tables” and “Component Properties” sheets. Now having all the information it needs, it unlocks the Buttons to obtain the Results Tables.

6.5.4 Results Tables

These must be obtained in a certain sequence. Some can be calculated immediately (Fuel Feeding, Head Loss, Syngas flowrates, Cooling Air and Hot Water), whereas others require results from other tables. Syngas is a particular case. Half of its data is necessary for the obtention of the Air Combustion and Fumes, but data from these, in turn, is needed to calculate the Syngas’ Heats. Therefore, the buttons will be unlocked in such a way that it forces the user to follow this order.

As most calculations are repeated and only require the lifting of data from the Raw Data Sheet, they are stored as functions which are called upon repeatedly. More complex functions will, however, also be stored in the same “Calculate Results” Module.

On pressing, each Button creates a Worksheet with its namesake.

Once all have been pressed, the purple boxes will be unlocked. These contain the buttons which return both the Mass and Energy Balance Sheets as well as the Comparison Graphs - the desired output.

6.5.5 Comparison Graphs

These graphs have been grouped into four groups:

- Gasifier reactor graphs (temperatures, head loss and air flowrate)
- Syngas’ line graphs (syngas and air temperatures, syngas and fumes flowrates)
- Boiler heat recovery graphs (water temperatures)
- Power graphs (various syngas’ Heats and fumes’ power)

Each group of graphs is drawn upon pressing the respective button and stored into a Worksheet of the same name.

6.5.6 Balance Sheet

By clicking on this Button the user will create a Worksheet containing all of the information presented above. Another Button, unlocked thereafter, allows the user to store the obtained information into the shown image. With this, the program is finished running.

6.6 Future Developments

This program employs a series of simplifications and procedures which, though generally not of major impact, may visibly affect the results.

The most glaring simplification is the use of an averaged value for the propane flow into the boiler. In trials where there is a substantial lack of syngas flow, the flow of propane will have to be regulated manually with some frequency. This fluctuation, if significant, will be clearly visible in the comparison graph. This is because it affects the calculations for the syngas’

power. A solution for this is to create an array, or table, where the propane flowrate at each interval is registered. The program would then use the values contained in this array for the calculations, thus eliminating this error.

Another simplification of a similar ilk is to do with the specific heats of the syngas' and fumes' components. These are taken to be constant and at ambient temperature. This is not the case. This variation is often not extreme for the most important components, only varying wildly with the minor ones (e.g. Ethane) - whose proportion and therefore impact is often negligible. As such, the approximation is a reasonable one to make. Nevertheless, the program could be used to calculate the specific heat of the components at each time interval, seeing as it possesses the temperature ranges of both the syngas and the fumes. It should be said that these specific heats would be approximations of their own, as there is little information about the operating temperatures in the boiler, and there are uncertainties related to the reactor's temperature ranges. However, they would be more accurate representations of reality. This development would be much more morose, as the formula used to approximate the specific heat for each component would have to be written into the code and applied at each instant - this would undoubtedly make the program much heavier and slower. Tests should be run to evaluate its usefulness.

The program lacks the option to skip certain steps, which could lead to having the engineer input information already present in the Treatment Tables. These should be implemented during a fine-tuning of the program.

The lack of flexibility is also a concern. Whenever the data from the trials is changed, the program will have to be changed directly in the code, the user interface being unable to cope with changes to the soon-to-be-analysed data. A similar phenomenon happens to the registering of results, these being written into specific cells or columns. Solutions to this issue should be pursued wherever possible.

Though it was decided to create each Results Table in separate Worksheets to allow for a clearer separation of values, this option is questionable. It creates a huge, and arguably unnecessary, number of sheets. Even if the option is maintained, at least routines should be created allowing for the grouping together of these Worksheets.

This program being in its earliest developmental stages, it will also contain bugs which may lead to it crashing. An example would be the closing of an Input Box before the information is inputted. Also, many procedures use overly complex and long code, which could be rewritten into much simpler and smaller segments. A later reworking of the program should focus on resolving these problems.

Chapter 7 Test-run using data from gasification trial

In this chapter both programs will be thoroughly tested: data from a specific trial will be taken, treated and analysed using both programs. This will also provide the opportunity to produce remarks on potential improvements, point out flaws or approximations and make a global evaluation of the work.

7.1 Trial

A gasification trial was conducted on the 12th of March of 2012. This trial will provide all the information needed to conduct this test-run. It must be said, that either for reasons of incompleteness or confidentiality, many of the inserted parameters do not correspond to reality. Nevertheless, this is of little importance as the point of this chapter is to see if the programs perform their functions appropriately, survey the results and draw conclusions. Considerations about the gasification trial itself are of lesser importance.

7.2 Data Processing

One begins by inputting the location of the Archives folder - containing all the .csv files from the trial - into the program (Figure 7.1). The parameters to be set are a Smoothing Number of 10, a Period of 15 with no Maximum Deviation and a Time-step of 1 minute. As was stated in Chapter 4, a Smoothing Number of 10, when paired with a high Period (>7) is sufficient for our purposes. The period has been set at a high value to ensure that no further smoothing will be necessary. The Maximum Deviation was disregarded. For the analysis of most trials the time-step chosen by the engineers is typically of 1 minute, and that is the reason for that choice.

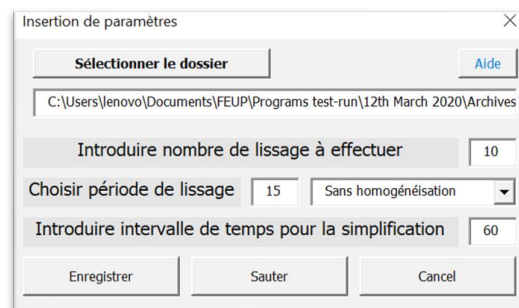


Figure 7.1 - Insertion of the essential parameters to kickstart the Data-Treatment Program.

The all-at-once route is chosen, seeing as there is no reason to run the program step-by-step in the treatment phase. Choosing this route takes the program around 3 minutes to complete the full array of processes. It must be mentioned that the Smoothing procedure is the heaviest one for the program. Indeed, this procedure alone accounts for around 50% of the time taken.

Table 7.1 - Time taken to complete the initial tasks one-by-one in the Data-Treatment Program.

<i>Process</i>	<i>Time taken to complete</i>
<i>Extraction</i>	35 s
<i>Smoothing</i>	100 s
<i>Creation of Raw Data Sheet</i>	5 s
<i>Simplification</i>	55 s
<i>Total</i>	195 s

To see if the results are already satisfactory, three of the most sensitive sensors are chosen: FT500 (syngas flowrate), FT600 (water flowrate) and PT501 (syngas pressure after passing the exchanger). The pre/post smoothing are presented in Figures 7.2 to 7.5.

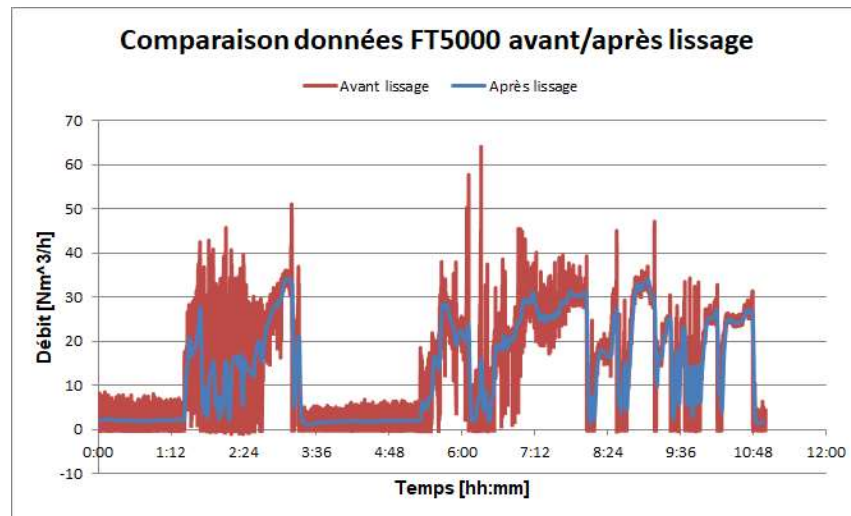


Figure 7.2 - Comparison of the FT500 collected data before (red) and after (blue) smoothing.

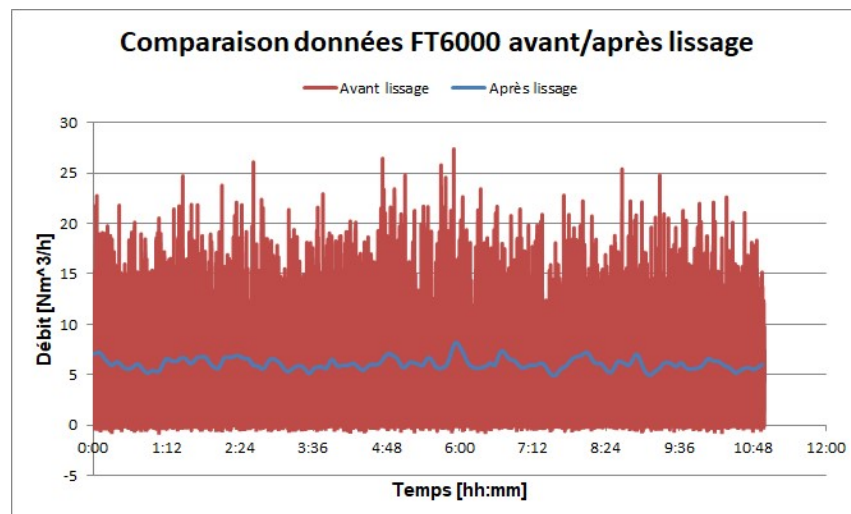


Figure 7.3 - Comparison of the FT600 collected data before (red) and after (blue) smoothing.

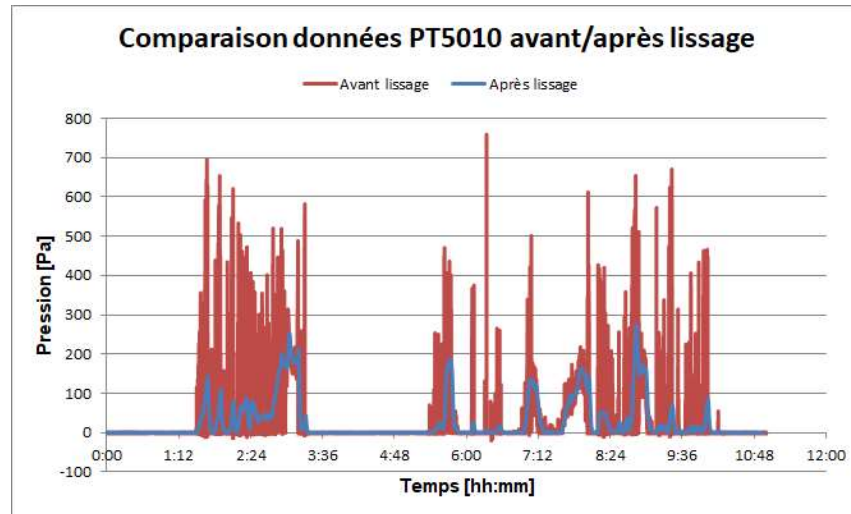


Figure 7.4 - Comparison of the PT501 collected data before (red) and after (blue) smoothing.

These curves were deemed satisfactory.

It is common for the gasification trial to take a bit more than an hour for the production of syngas to begin (this is owed to a pre-heating of the boiler and reactor). This is plainly visible in the FT500 graph. However, it is noticeable that the production was interrupted several times, with a particularly large interval during the 4th and 6th hour. To make the data more concise, these intervals will be deleted. It was decided that whenever the syngas flowrate falls below 7 Nm³/h the data collected at that moment is eligible for erasure. Although the first time interval is typically preserved (it informs on the time it took for the syngas production to begin - the pre-heating period), for the purposes of this paper all eligible intervals will be deleted. The results for FT500 and PT501 are shown below (Figures 7.5 and 7.6). This process is, as mentioned in Chapter 4, the one which takes the longest time for the program to complete. It will generally take around 7 minutes for it to finish. Here it must be reiterated that these times are dependent on the computer's processing power - one is more interested, therefore, in relative comparisons.

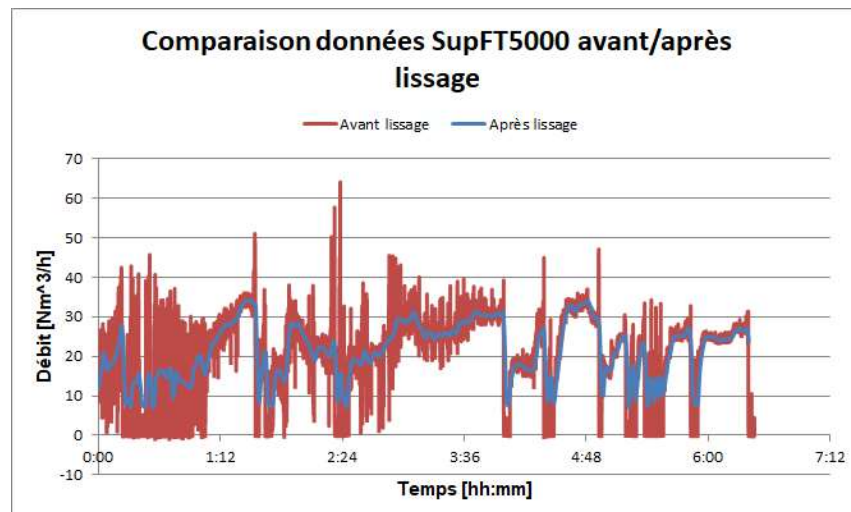


Figure 7.5 - Display of the smoothing effect (before in red and after in blue) for the FT500 after deletion.

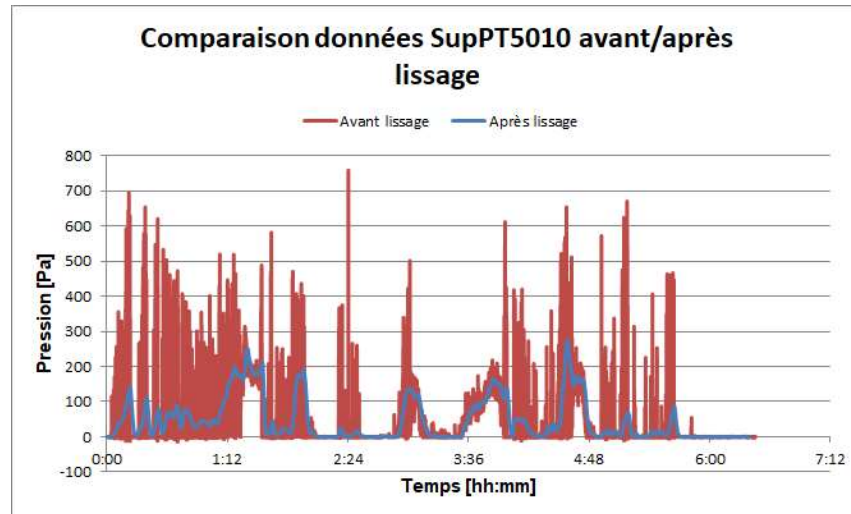


Figure 7.6 - Display of the smoothing effect (before in red and after in blue) for the PT501 after deletion.

Now in possession of the Deleted Data Sheet, this compilation of data will be passed into the Results-Analysis program.

7.3 Results' Analysis

The first step in using this program is to fill the preliminary tables. Some of the parameters are fixed, meaning that there is no need to edit them. Others, however, will vary according to the trial. It must be reiterated that not all of these parameters are essential for the proper running of the program - as such, for the purpose of concision, only essential parameters will be mentioned in this paper. These are in Table 7.2:

Table 7.2 - Parameters which must be registered into permanent Worksheets in the Results-Analysis Program.

<i>Treated waste</i>	<i>80% Biowaste pellets and 20% Wood</i>	
<i>Ambient Temperature</i>	20	°C
<i>Raw fuel feeding rate</i>	9.11	kg/h
<i>Fuel moisture</i>	12.20%	%
<i>LHV_{Fuel}</i>	19.63	MJ/kg
<i>Mass of recovered residues</i>	4.14	Kg
<i>Residue moisture</i>	0%	%
<i>LHV_{Residue}</i>	24.39	MJ/kg

The remaining information is important for the company's engineers, but it is not fundamental to the program's running, which is the focus of this work. Again, it must be stressed that some of these parameters are not real and only illustrative, the aim of this work being to test the program's capacity to return data quickly and efficiently.

After ensuring the proper filling of these preliminary tables, the location of the treated files is inputted. The Suppressed Time Intervals Data Sheet will be specified for extraction, as for the purposes of this chapter one wants to reduce the presence of malfunctions. The Sheet is then extracted by clicking the Extraction button.

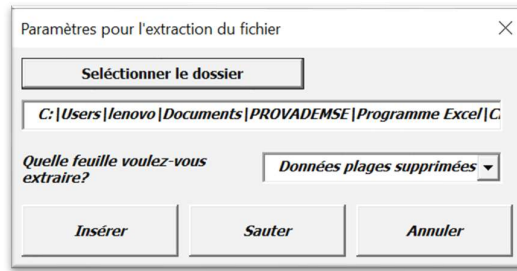


Figure 7.7 - Insertion of the location of the treated Excel file and specification of the type of sheet to extract.

The data needed to average the composition of both the syngas and fumes is obtained during the trial. After inquiring and acquiring the needed information (displayed in TABLES) it is introduced into the program and registered in the sheet “Treatment Tables”. This unlocks the Propane Flowrate Button, which is then inputted. This finalizes the input of information on the part of the user, the program now contains all the data it needs. To start the calculations the user must press the “Introduce Essential Parameters” Button and confirm he has verified that all the fundamental information is present.

Table 7.3 - Syngas’ composition (%V).

Syngas’ Composition (%V)

Components	%Humid	% Dry Base	% m
H ₂	4.87%	7.08%	0.40%
O ₂	1.53%	2.22%	1.99%
N ₂	42.38%	61.60%	48.29%
CH ₄	1.21%	1.76%	0.79%
CO	5.55%	8.07%	6.32%
CO ₂	9.63%	14.00%	17.24%
C ₂ H ₂ + C ₂ H ₄	0.89%	1.29%	1.96%
C ₂ H ₆	0.12%	0.17%	0.15%
C ₃ H ₈	0.01%	0.01%	0.02%
H ₂ S	0.00%	0.00%	0.00%
H ₂ O	31.20%	0.00%	22.85%

Table 7.4 - Combustion fumes' composition (%V and %m).

Combustion Fumes Composition

Components	Molar mass (g/mol)	%V	% m
O ₂	32.00	11%	11.72%
CO ₂	44.00	7%	10.49%
CO	28.00	0%	0.02%
NO	30.00	0%	0.07%
NO ₂	46.00	0%	0.00%
SO ₂	62.00	0%	0.00%
N ₂	28.00	77%	74.06%
H ₂ O	18.00	6%	3.64%
NO _x (= NO + NO ₂)	76.00	0.07%	0.18%
N ₂ + H ₂ O	46.00	82.41%	77.70%

With the mass percentage being calculated from knowledge of each element's molar mass.

Table 7.5 - Calculated syngas' properties.

Syngas' Properties	
ρ (kg/m ³)	1.09
C _p (kJ/kg/K)	1.28
MM (kg/kmol)	24.58
LHV _{ar} (MJ/Nm ³)	2.2620
LHV _{ar} (kWh/Nm ³)	0.628
LHV _{db} (MJ/Nm ³)	3.2878
LHV _{db} (kWh/Nm ³)	0.913

Table 7.6 - Combustion fumes' properties.

Fumes' properties	
ρ (kg/m ³)	1.2429
C _p (kJ/kg/K)	1.0554
MM (kg/kmol)	28.9444

Table 7.7 - Propane averaged properties.

Propane injected into boiler		
Flowrate	0.90	Nm ³ /h
Propane power	22.6350	kW

From this point onwards, all the Results Tables are obtained (Figure 7.8). This process takes, in total, around 20-30 s. Two examples are provided in Figures 7.9 and 7.10.

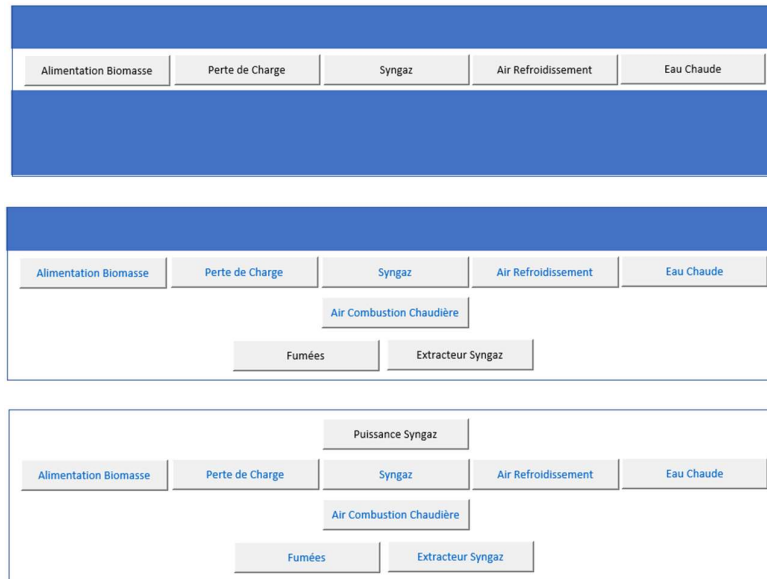


Figure 7.8 - Progressive unlocking of the buttons which create the Results Tables.

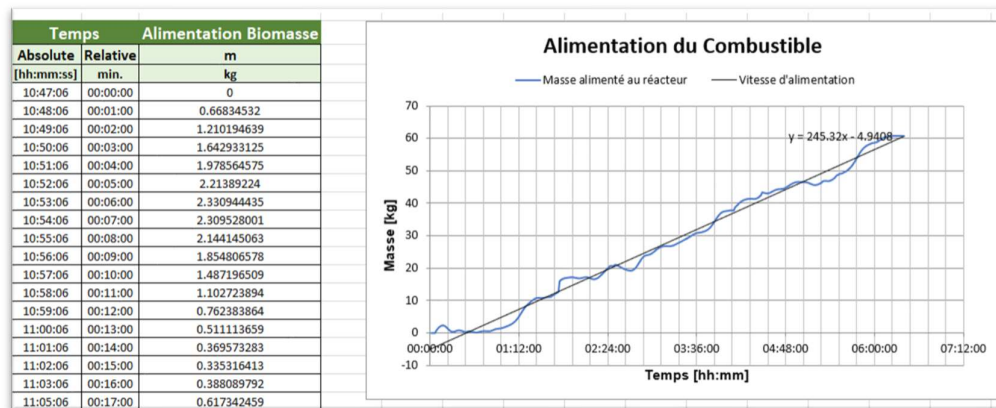


Figure 7.9 - Fuel feeding Results Table. This particular Worksheet also has a graph included in it.

[illegible]

Figure 7.10 - Syngas Results Table.

By consulting the Syngas' Results Table, one concludes that the flowrate was relatively stable from 02h50 to 04h00 (relative time). This period will be chosen as the Stable Regime Time Interval. It is then inputted into the program. The Balance Sheet is now obtained.

Component								
Sommes		Débit	Volume	Masse	Puissance	Énergie	Puissance Base PCI	Énergie Base PCI
		Nm3/h	Nm3	kg	kW	kJ	kW	kJ
Air Gazéifieur		1028.575802	61714.54813	79347.27617				
Syngaz		1985.250475	119115.0285	129406.7481	3828.181098	229690.8659	1478.596283	88715.777
Air Extracteur		3778.519293	226711.1576	291485.774				
Air Combustion		5988.050164	359283.0099	461935.2984				
Fumées	Théorique	2704.894838	162293.6903	201710.7703				
	Essai	8030.969605	481858.1763	598889.4809	392.3703537	23542.22122		
Moyennes		Débit	Débit Massique	%Volumique O2	Puissance	Énergie	Puissance Base PCI	Énergie Base PCI
		Nm3/h	kg/h	%	kW	kJ	kW	kJ
Air Gazéifieur	Pyrolyse	4.078860958	5.244249803					
	Oxydation	10.48503503	13.48075933					
	Réduction	0.13004404	0.16719948					
Syngaz		27.9612743	30.37717091					
	Hors Fumées				53.91804364	3235.082618	20.82529977	1249.517986
	P. transféré à l'échangeur				48.39170063	2903.502038		
	P. récupéré par l'échangeur à air				-2.079335917	-124.760155		
Air Échangeur		53.21858159	68.42389061		0.07812102	4.687261214		
Air Combustion		84.33873471	108.4355161					
		0.000976015	0.975859322					
Eau	Unité SI [L/min]	68.37878846	58551.55932					
	Théorique	38.0971104	47.34994609					
Fumées	Essai	113.112248	140.5843852	6.072794235	5.52634301	331.5805806		
	Émission à l'atmosphère	137.112248	170.4133852					

Figure 7.11 - Final Balance Sheet. The information contained in this table is subsequently used to fill in the Energy and Mass Balance Display.

Finally, the Energy and Mass Balance Display can be obtained:

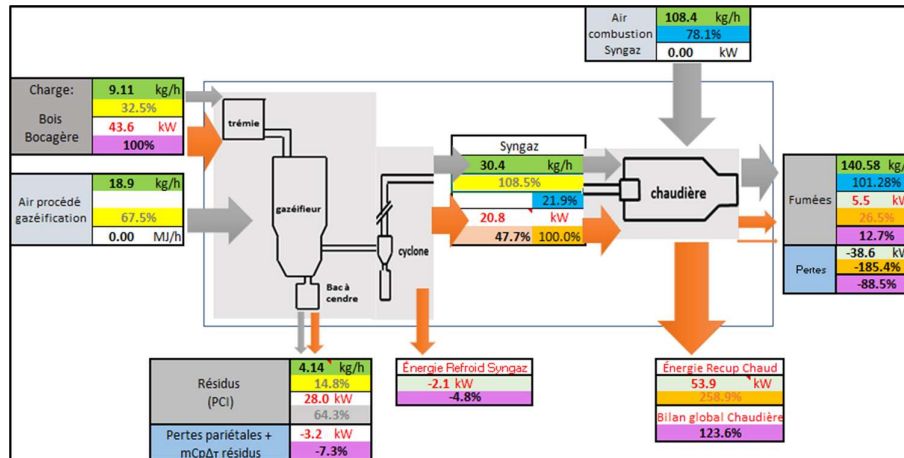


Figure 7.12 - Filled-in Energy and Mass Balance Display.

Again, it must be reiterated that these numbers and values are illustrative and do not accurately reflect the physical reality of the process.

It is instantly noticeable that some of these values are absurd. This is owed to the use of representative values where the measured ones were lacking. Nevertheless, it is noticeable that the program returned all the required data without hiccups, the whole process taking little over 30 seconds.

Though one is aware that many of these values will not offer a good representation of reality, one will nevertheless obtain the Comparison Graphs (Figures 7.13 to 7.19).

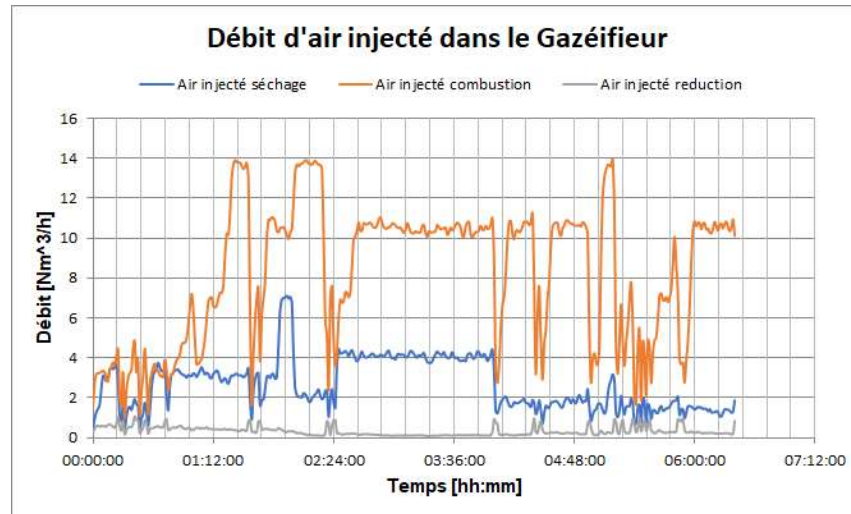


Figure 7.13 - Graph for the air flowrate into the gasifier.

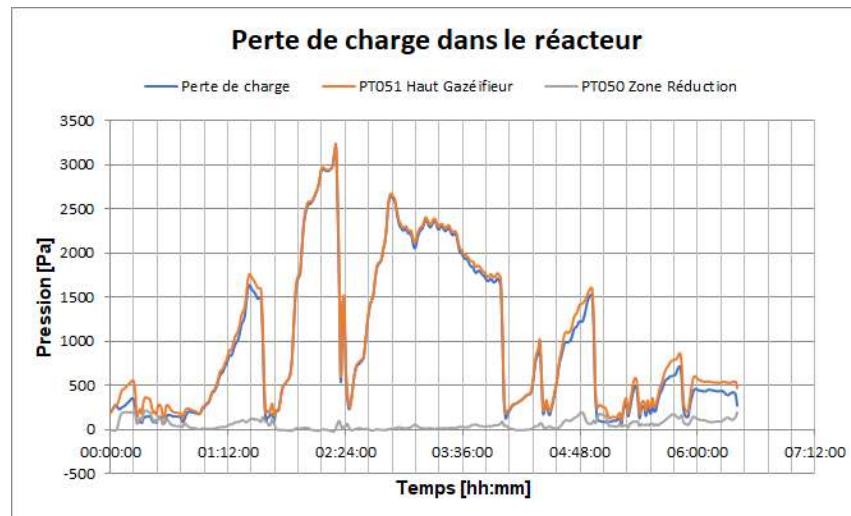


Figure 7.14 - Graph for the head loss in the gasification reactor.

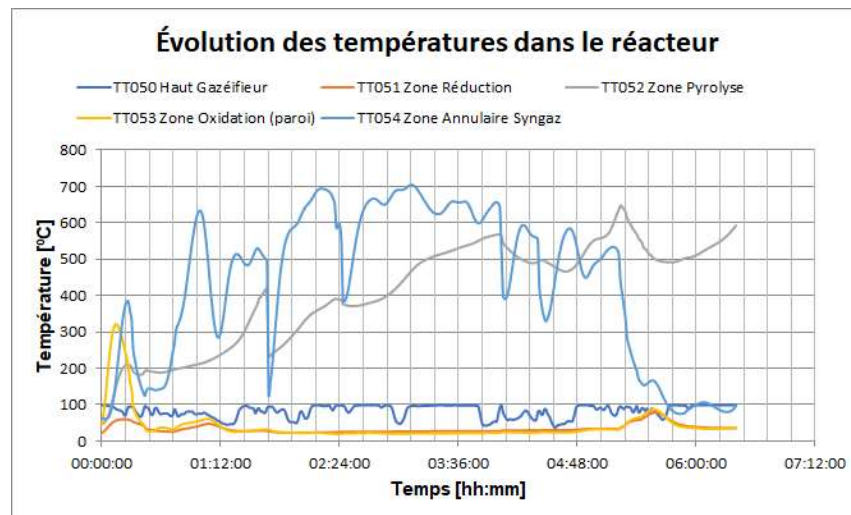


Figure 7.15 - Evolution of the zones' temperatures within the reactor.

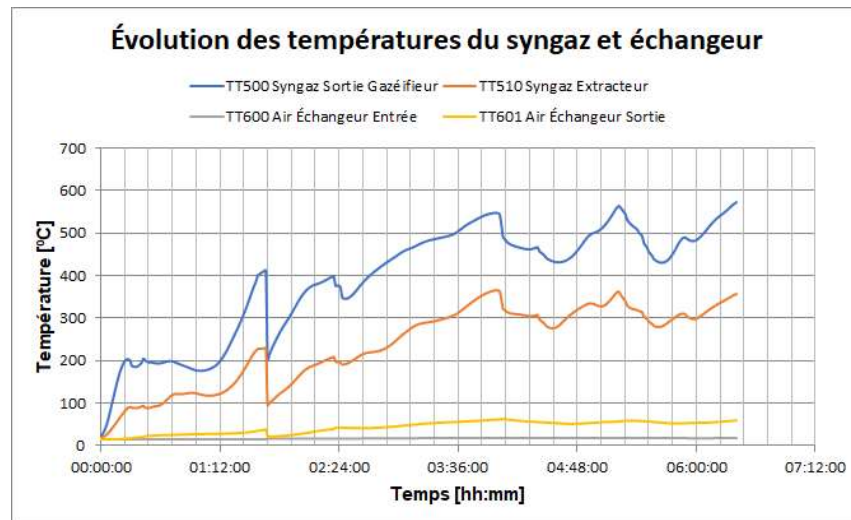


Figure 7.16 - Evolution of the syngas' and heat exchanger's air through time.

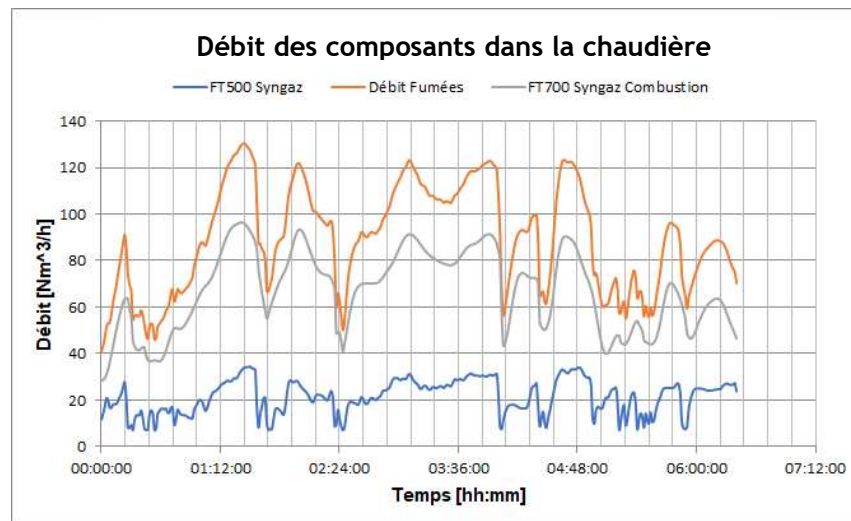


Figure 7.17 - Flowrates entering and exiting the boiler.

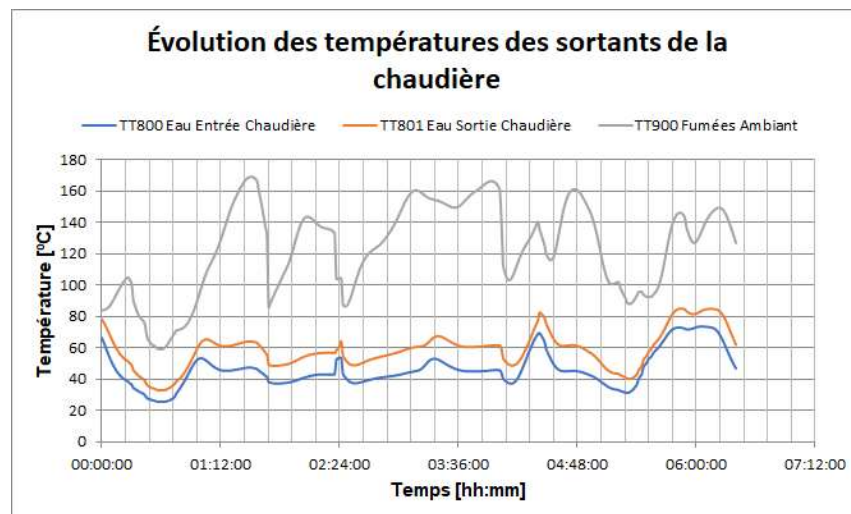


Figure 7.18 - Evolution of the temperatures of the components passing through the boiler.

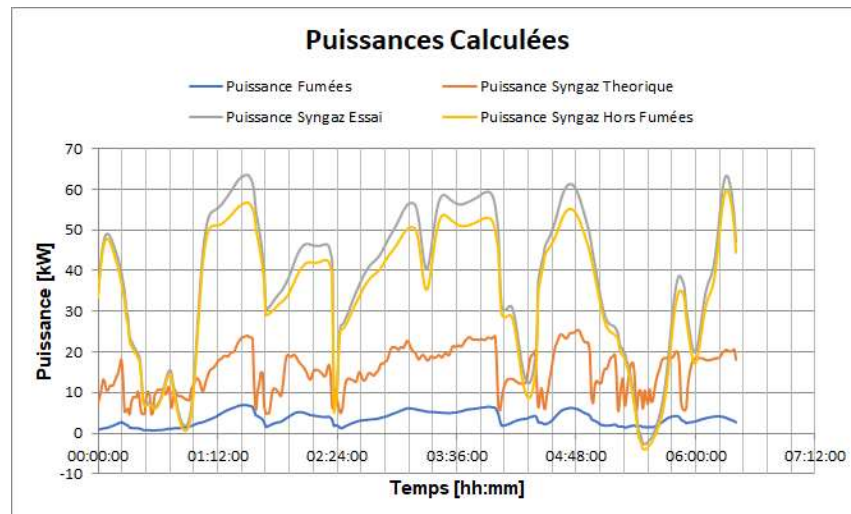


Figure 7.19 - Heats measured throughout the trial. It can be noted here that some error must have occurred with the measurements, as the measured syngas' power is often far above its theoretical maximum.

Having obtained the final product, one can now conclude that both programs could perform the required functions.

Chapter 8 Conclusion

Both programs could execute their functions and return the desired results without crashing. They executed their assigned tasks in a total of close to 15 minutes (the time of filling the tables notwithstanding). This represents an immense reduction in the time taken by the engineers to do these calculations bit-by-bit, from hours to mere minutes.

This test-run demonstrates decisively that there are great advantages to be had in developing programs that automate morose and complex calculations. Though they take a long time to develop and perfect, they very quickly return the investment by saving an immense amount of work and time to the engineers.

This project was eye-opening to the importance of mastering developer skills in today's fast and complex economy. It seems clear that proper fine-tuning of organisation, compilation and calculation tools acts as a great boon for companies which decide to invest in them - and their lack can quickly present a major weakness.

Finally, it also cast light on the complexity of thermochemical processes and the difficulty of extracting, sustainably, energy from renewable sources or from waste. It can be seen that only with major investment, research and technological maturation can these processes become widespread.

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