

Masters Degree in Chemical Engineering

Simulation and numerical optimization of diffusion-absorption refrigeration (DAR) cycle powered by solar energy

Masters Degree Thesis

Foreign Institution Development Project

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July 2009

Acknowledgments

Despite not working in a laboratory environment, which would probably have permitted me contact with a higher number of people during my daily life, I would like to emphasize that, in spite of not having many people to be thankful to in my project path; these few people really marked their presence in this project development during the whole semester:

I would like to thank Prof. Dr. Jean-Michel Reneaume for all the time that he invested in me, for all the explanations respecting the utilizable program, and for his precious advice and orientation during the project. Without his help this project could not be concluded.

To Prof. Dr. Pierre Cezac who managed to create a bridge between student and professor in which interest in me and my project were frequent. I am also thankful for all the clarification related to the thermodynamics of this project.

To my family, who have always tried to provide me with the best education over all these years and for giving me the opportunity of studying abroad, a fact that I have always considered of big importance in the life of a student. I am also thankful for their support and consideration during these months.

To all my friends who always gave me strength and who trusted in me, knowing me better than I know myself, respecting the way I dealt with this project and for their certainty that I would be able to finish it.

Abstract

This project was divided in two sections: the first one is related with the study of the parameters as total pressure, temperature of the evaporator and bubble pump, total flow rate and also mass fraction concerning the present components on the mixture used to refrigerate the diffusion-absorption refrigeration (DAR) cycle; the other sector consisted in optimize these parameters.

Through the behaviour of these parameters relatively to the coefficient of performance (COP) it is possible to say that to obtain a higher COP: pressure should decrease, the recuperation of butane in the bubble pump should increase and, since is in the evaporator that refrigeration happens its temperature should decrease. Mass fraction of butane should also increase and mass fraction of helium should decrease. The total flow rate does not contribute to the improvement of COP since that with its alteration COP remains constant.

This way knowing how the parameters should behave in order to achieve a better COP it was possible to proceed with the optimization.

After several tests the best optimization made resulted in a COP of 0.541 respecting all the conditions of the diffusion-absorption refrigeration (DAR) cycle.

This work showed that, with the right conditions, this could be a viable project.

Keywords: *coefficient of performance, diffusion-absorption refrigeration cycle, n-alkanes mixture*

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Notation and Glossary

Q_{ev}	heat for the evaporator	W
Q_{ab}	heat from the absorber	W
Q_{BP}	heat for the bubble pump	W
Q_c	heat from the condenser	W
COP	coefficient of performance	
T	temperature	°C
P	pressure	atm
Rec_{butane}	recuperation of butane	%
x_{helium}	mass fraction of helium	
x_{butane}	mass fraction of butane	
x_{nonane}	mass fraction of nonane	
□	total mass flow rate	kg/h

List of Abbreviations

DAR	diffusion-absorption refrigeration
EOS	equation of state
PR	Peng-Robinson
SRK	Soave-Redlich-Kwong
R21	chlorodifluoromethane 21

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1. Introduction

Absorption systems are extensively used in diverse applications related to climatic conditions and a detailed understanding of their working method is essential when searching for new ways or alternatives to improve the performance of these systems.

At the moment the rationing of energy resources is a distressing problem for several societal sectors, the positive influence of whom can play a significant part in engineering projects. These projects should be developed to combine minimal waste with the maximum profit achievable from energy sources.

By considering the wide applicability of these absorption systems as well as the trend of rationing energy resources, the idea of an absorption-refrigerated system which relies on alternative energy can be suggested. Since these types of systems do not need higher temperatures in order to work effectively, solar energy was implemented.

The refrigeration cycle is based on the long-known physical principle that a liquid expanding into a gas extracts heat from the surrounding substance or area.

The purpose of the refrigeration cycle is to remove unwanted heat from one place and discharge it into another. To accomplish this, the refrigerant is pumped through a closed refrigeration system. In an unclosed system the refrigerant dissipates into the surrounding media; however in this closed system, the same refrigerant is used over and over again as it passes through the cycle, removing some heat and then discharging it. Thus, there is no wastage of refrigerant. The closed cycle serves other purposes as well: it keeps the refrigerant from becoming contaminated and also controls its flow rate.

It is not possible to discuss refrigeration cycles without referring to their associated mixtures. As time has passed, machines based on different refrigeration cycle concepts have been developed, as have their associated mixtures. The upgrade of refrigerated cycles is directly connected to the variety of mixtures used and, more concretely, with the refrigerants used.

The list of desired refrigerant properties is extensive. In addition, to have good thermo-physical properties, an ideal refrigerant should be non-flammable, non-toxic, stable inside the system, and with harmless decomposition products once outside the system. Practical considerations call for low cost and full compatibility with system materials including lubricants and machining fluids.

Another important aspect, which involves both refrigeration system and its refrigeration mixture, is their decreased environmental impact. The preservation of the environment is a factor that should always be considered in engineering projects.

Every day new configurations related to refrigeration systems appear in order to transform these cycles into better and “cleaner” projects. With the passing of years refrigeration cycles are being changed and several devices which are a part of these systems are being modified, replaced or even removed from these systems. Now, the main purpose is to change them in order to become simpler and “clean”. This can be done since their mixtures are also changing in order to prevent environmental impact. Because of this, devices which purify or neutralize the mixture are unnecessary as the mixture does not have secondary effects and does not need special treatments to work in the cycle. Environmental impact is also tested in the mixtures, especially in the refrigerants.

In the past, the use of many refrigerants was stopped due to their detrimental effect on both human health and the environment. They were either toxic or flammable, or both. Accidents were common and the need for new safe refrigerants became obvious.

Refrigerants such as ammonia, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and sulphur dioxide were replaced by others called “environmentally accepted working fluids”. Although these compounds are better for the environment their efficiency needs to be optimized. There is constant research on this subject and several modifications are currently being made in order to improve their performance.

To measure the performance of a refrigeration cycle the coefficient of performance, defined as the ratio of work or useful output to the amount of work or energy input, is used. A higher COP means a higher efficiency of the equipment.

The main purpose of this project consists of a new refrigeration cycle considered “clean”.

Due to the fact of also being an extremely simple refrigeration cycle based on an absorption-diffusion principle, this system is composed of a condenser, an evaporator and an absorber, a heat exchanger and a bubble pump.

The fact remains that to have the same total pressure in every point of the cycle any type of pressure bomb or compressor is not needed.

The mixture used in this system is constituted by the working fluids butane and nonane; and helium is used here as the inert gas.

Butane is used as refrigerant while nonane works as the absorbent. Helium, which works as an inert gas, is used to maintain constant the total pressure of the system.

Since an absorption-diffusion refrigeration cycle is still known as a recent development, due mainly to their applicability range which still has a lower coefficient of performance (COP), new solutions were suggested as ways to improve the performance of the cycle. These new solutions were tested through simulation and the program used was ProSim Plus, version 2.1.

2. State of Art

2.1 Types of refrigeration systems

Refrigeration systems fall into two main categories: those that require mechanical energy or its equivalent in order to operate, mechanical refrigeration systems, and those that consume essentially thermal energy, thermal refrigeration systems.

2.1.1 Mechanical refrigeration systems

2.1.1.1 Vapour compression refrigeration system

The vapour compression refrigeration cycle is still the most widely used system concerning refrigeration⁽¹⁾.

This cycle constitution includes a compressor, condenser, an expansion device and an evaporator. All the devices are connected between them with a working fluid that circulates inside the system. For having thermodynamic properties that adapt them to be used in refrigeration systems, these working fluids can also be called by refrigeration fluids.

So the described path by working fluid, also called refrigerant, starts with a compression by a mechanical compressor and then it goes to the condenser where is liquefied. The liquid formed enters in the evaporator through an expansion device and its vaporization produces useful cooling.

2.1.1.2 Gas refrigeration system

In these systems, the working fluid remains in the gaseous phase.

The compressed gas heats up and is then cooled under a lower pressure (lower than the pressure that exists in the system). Next, the gas is expanded, cooling down the system.

The development of these systems has been hampered by their reduced efficiency, compared with the vapour compression systems. Their reduced efficiency is applied to refrigeration, freezing and air-conditioning fields. However, gas cycle systems are used in most cryogenic cycles in order to liquefy gases and produce lower temperatures.

2.1.2 Thermal refrigeration systems

2.1.2.1 Absorption refrigeration system

Although the use of these systems is not widespread, compared with compression systems, absorption refrigeration cycles are the only thermal refrigeration systems that are still in a progressive development.

In these systems, instead of using a mechanical compressor to circulate the refrigerant, a pump is used to make the liquid absorbent circulate.

The mechanical work is reduced however, heat is still required.

Generally speaking, the absorption refrigeration cycle works due to absorption and desorption of the refrigerant fluid contained in a liquid solution.

The absorption refrigeration cycle performs the heat exchanges that allow the conditioning of the environment. During the absorption process there is a heat transferred between the surrounding environment and the cycle. During the desorption process heat is provided to the cycle through a high temperature heat source⁽²⁾. This system is shown in figure 1.

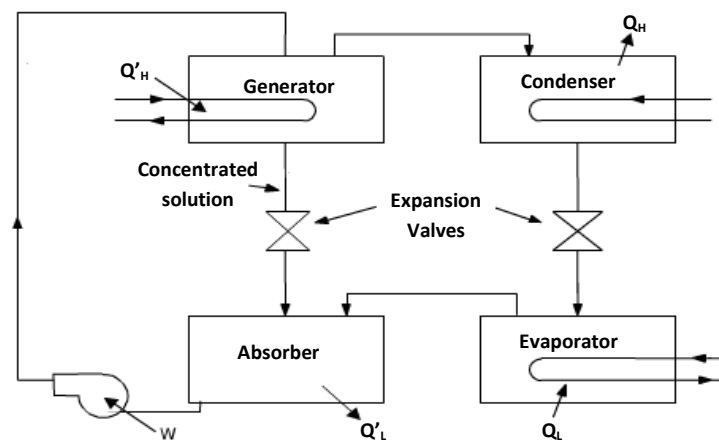


Figure 1 - Absorption refrigeration cycle

The absorption cycle is mainly composed by four processes, two of them characterized by simultaneous exchanges of heat and mass. These processes and its components, presented in figure 1, are the following:

- Generator: where the separation (desorption) of the refrigerant from the absorbent substance occurs;
- Condenser: where the refrigerant is condensed; in this device there is a heat transference from the cycle to the surroundings;
- Evaporator: where the physical state of the refrigerant changes from liquid to vapour due to the transferred heat from the region that needs to be cool down;
- Absorber: where the refrigerant is absorbed by the absorbent substance with heat transference to the surroundings;
- Expansion valve: which is used to reduce the pressure of the refrigerant from the condenser level to the evaporator level;
- Pump: responsible for the transference of the poor mixture from the absorber to the generator.

In these cycles the exchange of heat in the evaporator (Q_L) can occur by direct or indirect expansion:

- a) The heat exchange by direct expansion takes place when the fluid used for exchange is the fluid that needs to be cooled down which, in this case is air.

Examples of direct expansion systems: small port air conditioning systems (self-contained and splits).

- b) The heat exchange, by indirect expansion, occurs when there is an intermediary fluid to the heat exchange, in most cases is water or solutions with a lower freezing point.

The water is cooled down in the evaporator then chilled water is pumped to fan-coils where the air is cooled down and insufflates in the environment. These refrigeration units are called chillers.

Examples of indirect expansion systems: medium to high port air conditioning centrals.

Another variant that can also be applied to absorption refrigeration cycles concerns a number of generator stages. These cycles can perform in a single-effect or multi-effect system.

The main objective of a higher effect cycle is to increase the performance of the cycle when a high temperature heat source is available ⁽³⁾. By the term “multi-effect”, the cycle has to be configured in a way that heat rejected from a high temperature stage is used as heat input in a lower temperature stage, for generation of additional cooling effect in the lower stage.

The studied cycle, diffusion-absorption refrigeration cycle, is integrated in absorption refrigeration cycle. For this reason this sub-chapter is more developed when compared to the others. Most part of the subjects explained above can also be applied to the studied cycle.

2.1.2.2 Adsorption and thermochemical refrigeration system

Adsorption and thermochemical systems were developed later than other referred systems. These systems started to appear essentially during the first half of the 20th century ⁽⁴⁾.

The operating principle based on thermal effects accompanying the physical sorption or desorption of a gas into a solid (adsorption systems), or the formation or breakdown of chemical compounds using a gas refrigerant (thermochemical systems).

These kinds of systems are discontinuous and its use is practically null due to a lack of investigation in this area ⁽⁵⁾.

2.1.2.3 Ejection refrigeration system

These systems operate using cooled water that changes into vapour at low pressure; the vapour is then sucked using an ejector that is fed by a steam jet supplied by a boiler. The ejector comprises a combining nozzle – raising the flow rate of the jet reduces the pressure, enabling the desired degree of suction to take place. The gradual increase in the diameter of the delivery nozzle reduces the flow rate and the pressure rises again. Despite these systems have a specific application it is still far from being widely used.

2.2 Original diffusion-absorption refrigeration (DAR) cycle and its precedent alterations

The diffusion-absorption refrigeration (DAR) cycle invented in the 1920s was based on ammonia (refrigerant) and water (absorbent) as the working fluids together with hydrogen as an auxiliary gas. Since there are no moving parts in the unit, the DAR system is both quiet and reliable. The system is, therefore, often used in hotel rooms and offices⁽⁶⁾.

Several systems have been manufactured based on the original DAR cycle⁽⁷⁾ with the following variations:

- The type of flow inside the evaporator and the absorber may be in counter flow or parallel flow;
- The gas heat exchanger may be attached to the evaporator;
- The weak solution may flow in the shell or in the tubes of the solution heat exchanger;
- The condensed ammonia may be sub-cooled;
- The inert gas could be hydrogen or helium (helium has been started to be used as the inert gas due to safety reasons).

There is still a continuous research in this area in order to alter the system and, consequently, to improve the performance of the cycle.

The original system started to be modified by including a heat exchanger in the generator⁽⁸⁾. The working fluids were ammonia-water-hydrogen. The system with the new generator demonstrated a significant improvement in the cooling COP of 50% when compared to the original system.

A new experimental unit was manufactured also based on the original refrigeration cycle⁽⁹⁾ with the working fluids ammonia-water-helium.

The results from the developed mathematical model of the cycle were compared with the experimental results and showed that the system performance is strongly dependent upon the bubble pump characteristics as well as the absorber and evaporator mass transfer performance.

Subsequently, a thermodynamic model was developed for an ammonia-water diffusion-absorption refrigerator whose inert gas was hydrogen or helium⁽¹⁰⁾.

The performance of the cycle was investigated by computer simulation and their results showed that the system operating with helium, as the auxiliary gas, presented the coefficient of performance up to 40% higher than a system working with hydrogen.

2.3 Implementation of solar energy in refrigeration systems

The necessity of implementing self-sufficient cycles, with regards to its energetic resources, is an important issue which affects reduction of the environmental impact.

Clean refrigeration cycles that do not need to consume fossil fuels and, as a consequence, do not emit polluted gases. This fact, allied with the idea of having the ability to put these systems in the most remote areas and giving the possibility for everyone to be able to enjoy it are important factors in a way to find a solution to improve this system. The idea of using solar energy was starting to arouse interest.

Solar cooling systems are actively being developed these days. The motivation of the renewed interest in solar cooling systems includes the increase in energy prices, environmental considerations. The economic feasibility of such systems is the controlling factor for successful commercialization⁽¹¹⁾.

Absorption diffusion refrigeration system seemed to be a promising system for the application of solar energy⁽¹²⁾. In this study, the design of a commercially vapour absorption electrical refrigerator was changed to make it suitable for running with solar energy. The system was tested and operated in Shebin-El-Kom, Egypt. The system coefficient of performance was estimated in 0.02.

In order to evaluate the potential of different solar cooling systems, a classification was made based in three main concepts: solar collectors technologies, technologies for cold production and specific uses⁽¹³⁾.

The solar technologies considered relevant are:

- Flat plate collectors;
- Evacuated tubes;
- Stationary non-imaging concentrating collectors such as CPC;
- Dish type concentrating collectors;
- Solar ponds;

- Photovoltaic systems;
- Thermoelectric systems.

For most cooling technologies temperatures near 100°C are required. The success of solar cooling is strongly dependent on the availability of low cost and high performance of solar devices.

Solar energy is becoming more and more recognized as a priority in developed countries ⁽¹³⁾.

2.4 Development of the mixtures applied in the refrigeration cycles

From the beginning of the 19th century, machines based on different refrigeration cycle concepts which use a variety of refrigerants were proposed. The majority of them disappeared from use when better alternatives were implemented. For almost two centuries, the stimulus for these changes was a growing market demand for “artificial cold”, development of component technologies, economics and personal safety.

Three American corporations launched collaborative research to develop a safer method of refrigeration and their efforts lead to the discovery of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) ⁽³⁾. After their introduction in 1930, CFCs and HCFCs gradually became the preferred refrigerants for most applications with ammonia and air obtaining common presence in liquid chillers and aerospace applications. The dominating market share of CFCs and HCFCs was a result of their favourable attributes including safety and high efficiency.

The domination market position of CFCs and HCFCs was unchallenged until their implication in the depletion of the ozone layer. At the time an intense research started to find alternative working fluids.

A list of the desired refrigerant properties is extensive. As it was already spoken, to have good thermo physical properties, an ideal refrigerant should be non-flammable, nontoxic, stable inside the system and unstable in the atmosphere with harmless decomposition products.

The most popular refrigerants that were later used commercially for some extended time were carbon dioxide, ammonia, sulphur dioxide, methyl chloride and isobutane. Carbon dioxide was known, in that time, for its low efficiency. The other refrigerants were either toxic or flammable, or both. Accidents were common and the need for new safe refrigerants became obvious.

In these days, considered the limited information found in the published literature, the research started to turn to the periodic table of elements. It was realised that all refrigerants used at that time included a small group of elements that were located closed to the upper-right corner of the periodic table: carbon, nitrogen, oxygen, sulphur, hydrogen, chlorine and bromine.

The layout of the elements on the periodic table allowed observing definite trends in reactivity, volatility, toxicity and flammability of compounds involving different elements. Thereby, fluorine was considered because while fluorine was known to be toxic, there was a suspicion that fluorinated compounds were nontoxic. So fluorinated compounds were focused and rapidly appear the first synthesized, chlorodifluoromethane (R21), for initial evaluations. A methodical evaluation of a large number of fluorochemicals continuous and after a few time R12 and R11 appeared in the market. By the 1950s, with the introduction of other compounds, fluorochemicals became the dominant refrigerants in vapour-compression systems. Ancient used refrigerants were abandoned except ammonia, which still retains a notable position in water-chilling applications.

Nowadays the main effort is focussed on researching mixtures with no environmental impact at the same time that still can provide a higher performance.

3. Results and Discussion

The beginning of this project consisted of research and a consequent study of the main refrigeration cycles and their associated mixtures regarding their feasibility. The study was made based on the following parameters: structure and devices of cycles, power consumed, stability of mixtures and COP values.

The considered cycles were a refrigeration cycle built by Einstein ⁽¹⁴⁾ and its more recent configurations ⁽¹⁵⁾; refrigeration cycles based on the principles of Rojey and the several mixtures which could be adapted to each one of these cycles ⁽¹⁶⁾; and finally the more recent refrigeration cycles whose main characteristics, as well as their associated mixtures, are related to the environment ^{(17) (18)}.

This study helped in a way that it was possible to make important conclusions due to the established conditions for each cycle as well as the adequate treatment concerning each cycle and their associated mixtures.

Towards to this it was permitted a better understanding related to the practicability of the cycle in question.

3.1 Diffusion-absorption refrigeration (DAR) cycle

A diffusion absorption refrigeration (DAR) cycle is driven by heat and use a binary solution of refrigerant and absorbent as working fluid, butane and nonane, together with auxiliary inert gas helium. Ecologically speaking relatively to butane it can be said that, in terms of polluting water and soils its penetration it is practically null and it is also a compound that do not have adverse effects to the environment ⁽¹⁹⁾. Helium is also a compound that shows the same environmental behaviour ⁽²⁰⁾.

Relatively to nonane, this compound does not bring any risk concerning the human health however, has a lower risk concerning contamination in aquatic environment ⁽²¹⁾. Spite of being lower, special treatment must be taken in account.

This cycle is operated by thermal energy not requiring electrical or mechanical energy. DAR cycles advantages consist of having no moving parts like pumps or fans; silent operation and portability, using any kind of heat source.

Beyond these advantages, this kind of systems exhibits good reliability, durability and minimal maintenance costs.

This cycle can use as external fluids water or air to cool down the butane that enters in the condenser. In case of using water its temperature should be around 25°C and in case of air of 35°C.

Generally temperatures for condensation should have a minimal temperature delta of about 12 to 15°C relatively to the cooling with air and a minimal temperature delta of 5°C in case of using water to cool down. Although, it should not be forgotten that higher the delta higher the efficiency.

The only external source of power in this cycle is the heat provided to the bubble pump. Since is not needed a really high temperature for this equipment to work effectively, solar panels were implemented to reach the desirable temperature in the entrance of the bubble pump.

The refrigeration cycle, crucial point of this study, is presented in figure 2.

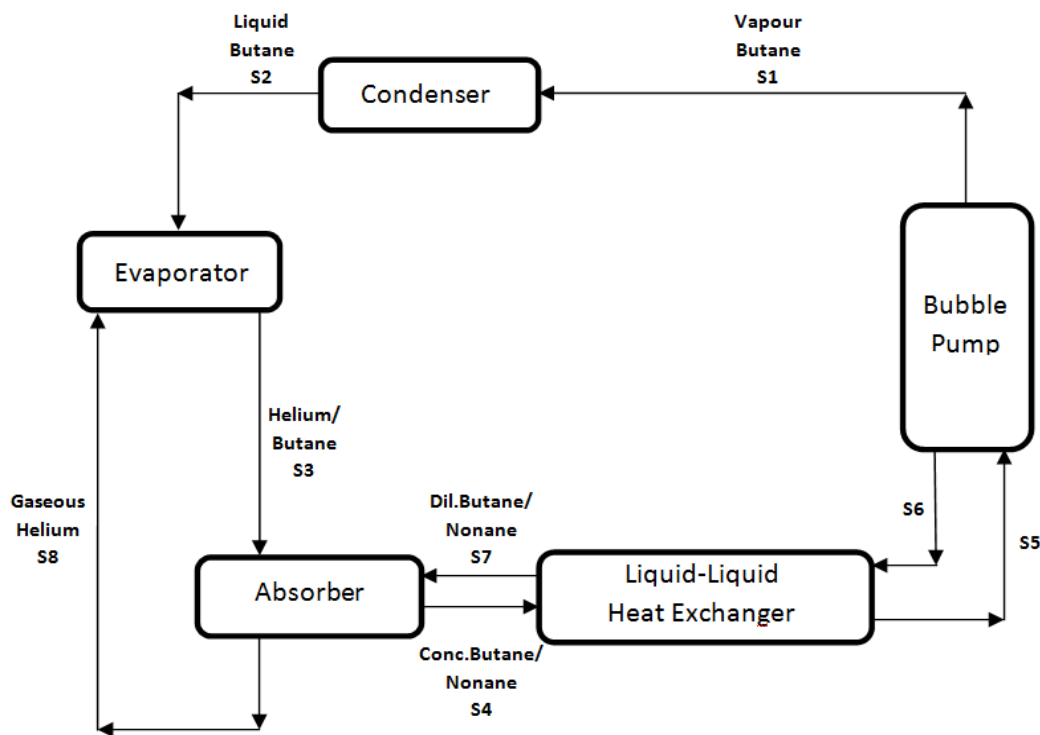


Figure 2 - Scheme of the diffusion-absorption refrigeration (DAR) cycle

The fact of not using external fluids in the heat exchanger and having only one source of heat turns this cycle really simple. The description of the cycle consists in: a condenser, a bubble pump, a heat exchanger, an absorber and an evaporator.

Now, it will be shown in detail how this cycle works.

Starting by the stream 1, the butane gas enters in the condenser transforming it in a saturated liquid. The heat resulting from this modification is called Q_c . After passing the condenser, liquid butane goes to the evaporator, who needs a power supplied called Q_{ev} . Helium is provided to the evaporator also.

There is an intern cycle between the evaporator and the absorber whose main goal is to obtain a partial vaporization of the butane. Then, the solution goes to the absorber and the thermal

conditions and the concentration of nonane is such that butane is absorbed in high quantity, rich solution. This rich solution, stream 4, follows to a liquid-liquid exchanger to be heated by a cross-stream coming from the bubble pump. The principal meaning is to get a liquid-gas mixture in order to flow up (gas-lifting) through the bubble pump, stream 5. In the bubble pump, a gas phase consisting essentially of butane vapour is extracted. The poor solution of butane content returns to the liquid-liquid exchanger to heat the solution from stream 4 and then it goes to the absorber to absorb more butane.

Unfortunately, this cycle is still known for its lower efficiency. This way, tests were made concerning the parameters of the cycle in a way to understand how significantly their change can be to the performance of the cycle.

In the beginning each variable was studied separately to verify their properly range. This range should not interfere with the devices itself and either with the behaviour of the cycle concerning its suitable functioning. This study was made through extensively research.

3.1.1 Analytical model

The analytical model from de DAR cycle was developed under the following conditions:

- Since the main purpose of the condenser was changing the physical state of butane from saturated vapour to saturated liquid, the input and output streams remain with the same temperature,

$$T_1 = T_2 \quad (1)$$

- In the evaporator the temperature of the two inlet streams is the same,

$$T_2 = T_8 \quad (2)$$

- The temperature of the poor solution, constituted by butane and nonane, was assumed to enter in the absorber 5°C higher than the temperature of the rich solution (leaving the absorber),

$$T_7 = T_4 + 5^\circ\text{C} \quad (4)$$

- The total pressure of the system is $P_{\text{total}} = 4.9 \text{ atm}$ (5) and pressure drops along the pipes were neglected;

- Relatively to the properties of the mixture they were calculated according to an ideal mixture;
- The heat power provide to the evaporator was assumed to be 1000W (6);
- Recuperation of butane in the bubble pump was assumed to be 90% (7);
- Due to previous tests made in order to verify if the cycle was working correctly it was decided to fix the mass fractions in the referred values: $x_{\text{nonane}}=0.35$ (8), $x_{\text{butane}}=0.52$ (9) and $x_{\text{helium}}=0.13$ (10);
- Mass total flow rate was assumed to be 100 kg/h (11).

3.2 Coefficient of performance

3.2.1 Thermodynamic model – equation of state

Initially it was tried to find the interaction parameters between the components of the studied mixture. Unfortunately it was not possible to obtain them since the studied mixture is still very recent and there is not enough information.

Due to this fact it was necessary to adapt a usual equation of state (EOS) to the studied mixture.

Several equations of state were tested in order to see which one verify the appropriated characteristics to the DAR cycle. Unfortunately, the most part of the tested equations of state did not worked correctly in the cycle presenting unusual behaviour in some streams. Only two equations of state verified the necessary characteristics to the good functioning of the cycle: Soave-Redlich-Kwong (SRK) and Peng-Robinson (PR) state equation.

In order to obtain a comparison between the two EOS it was necessary to compare their coefficient of performance (COP).

The coefficient of performance (COP) is defined as the ratio between the removed heat through the evaporator (thus creating the refrigeration effect) to the heat supplied to the bubble pump,

$$COP = \frac{Q_{ev}}{Q_{BP}} \quad (1)$$

A higher COP means more heat absorbed by the evaporator and, consequently, higher refrigeration.

After testing both equations of state in the cycle, the values of the COP were obtained for a posterior comparison, table 1.

Table 1 - Coefficient of performance of Soave-Redlich-Kwong and Peng-Robinson equation of state

Equation of State	COP
Soave-Redlich-Kwong	0.4018
Peng-Robinson	0.3857

From the results presented above it can be seen that the SRK state equation has a better COP when compared to PR state equation. Actually these two equations of state are pretty close to a tie except to the slightly better behaviour of PR EOS at critical points. Since PR EOS improves the performance around critical conditions this makes the PR EOS somewhat better suitable to gas/condensate systems. So, spite SRK EOS has a higher COP for this project, it was chosen PR EOS because it works better with condensable fluids giving more trustable results^{(22) (23)}.

3.2.2. Study of the parameters

To study and improve the efficiency of the coefficient of performance (COP) research was made relatively to the parameters of the cycle and their influence in the behaviour of a DAR cycle.

Parameters as total pressure of the system, recuperation of butane, total flow rate, mass fraction of each component, temperature from the bottom of the bubble pump and also temperature from the outlet of the evaporator suffered alterations.

These alterations were made through simulations in a way to verify the importance of each parameter in the efficiency of the cycle and, consequently, to the obtainment of a better COP.

For each modified parameter the others were fixed in value previously assumed. These assumptions were made in order to start simulation and its values are present in the next table.

Table 2 - Assumed values for the initial parameters

Parameter	Assumed value
$Q_{ev}(W)$	1000
$P_{total}(atm)$	4.9
$T_{s4}(^{\circ}C)$	50
$T_{s8}(^{\circ}C)$	50
Rec.butane(%)	90
x_{nonane}	0.35
x_{butane}	0.52
x_{helium}	0.13

These values, with exception to mass fractions and butane recuperation on the bubble pump, were removed from a previous study made in the same area⁽¹⁸⁾.

The values of mass fractions and recuperation of butane were assumed regarding the feasibility of the cycle.

This table indicates that every time that one of the parameters above was changed to study its influence in COP the others will remain in the presented values.

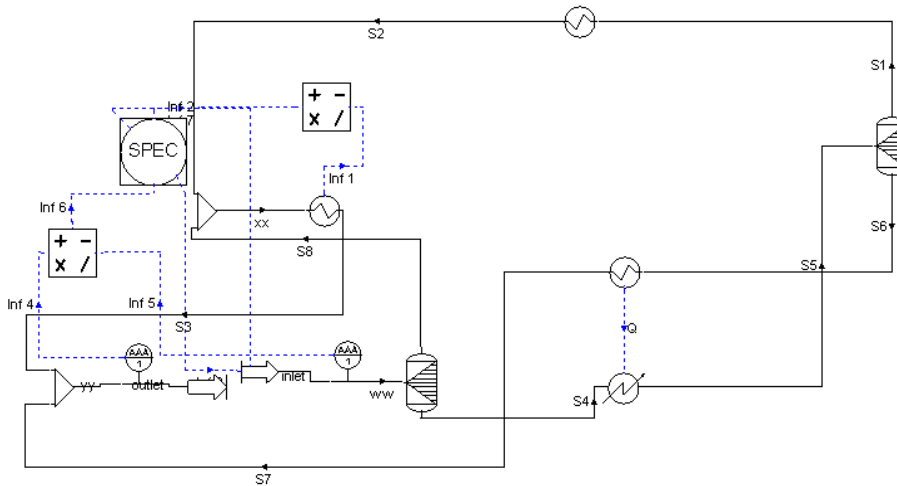


Figure 3 - Simulated cycle in ProSim Plus

The first studied parameter was the total pressure of the system. Pressure was modified in a range of 4 to 6 atmospheres, unfortunately only the range from 4 to 5.2 atmospheres showed trustable results. As trustable results it means the correct physical states of all the streams as well as the mass and energy balance (annex C), and also plausible temperatures considering specific devices as the bubble pump and the evaporator.

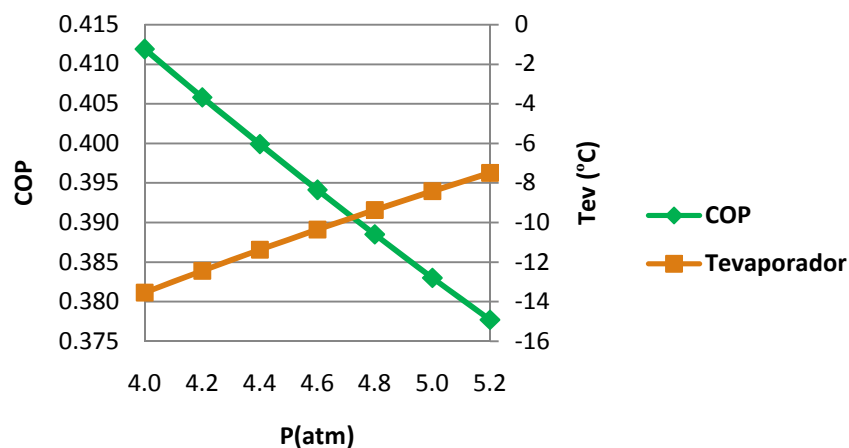


Figure 4 - Total pressure of the system versus coefficient of performance and evaporator outlet temperature

The pressure of the DAR cycle is total and, for that matter, this cycle does not need other devices like pressure pumps or even compressors to compensate the difference of pressure.

Observing figure 5 it can be verified that COP increases with the decrement of pressure so, the total pressure of this system should be maintained in the lower value that is possible.

Since pressure is the same in every point of the cycle, considering all the streams and equipments, this behaviour could be explained by the fact this parameter do not verified a significant impact concerning to COP.

Another factor that should always be considered in the study and modification of each parameter is the outlet temperature of the evaporator. This is an important parameter since is the evaporator that permit the cooling down of the environment. Small alterations concerning any variable and the evaporator can start acting like a heater instead of a refrigerator.

In this range of pressure the evaporator outlet pressure spite its raise with the raise of pressure continues to be negative which means that the evaporator is cooling down.

In the figure presented above it is verified also that the lower temperature concerning the outlet of the evaporator leaves to a higher COP and, consequently, a higher refrigeration. This behaviour is related to the proximity of the ambient temperature so, a lower temperature means more cold and more ability to cool down the air from the outside system.

Another topic that should also be considered refers to the temperature of the bubble pump. Since temperature cannot be a fixed variable its study is made in function of the other parameters.

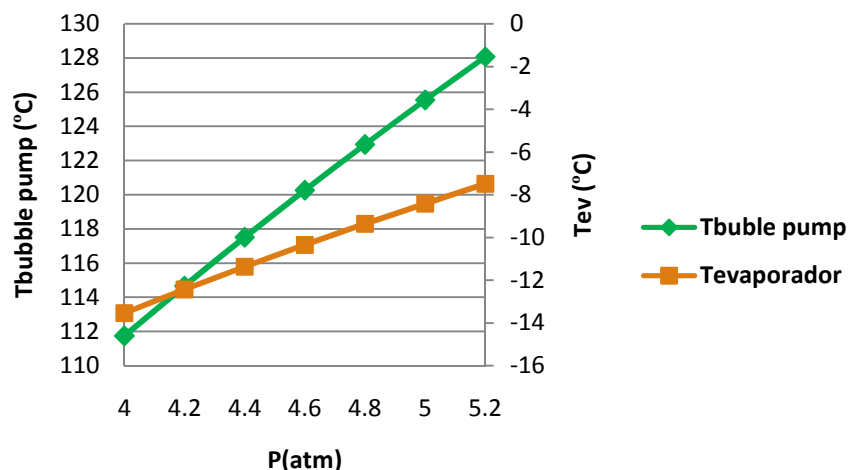


Figure 5 - Total pressure versus temperature from the bottom of the bubble pump and outlet temperature of the evaporator

In this figure is permitted to study the behaviour concerning the raise of temperature, whether in the evaporator or in the bottom of the bubble pump, with pressure. Since both lines do not have a significant interval between the values it can be seen that for this range of pressure, temperature does not seem to have a significant influence.

Since the pressure of the cycle should be focussed in a lower pressure, in this figure is also implicit that lower temperatures for both devices also contribute to a COP improvement.

This way from the bubble pump till the evaporator is provided the necessary cooling that permits efficient refrigeration, with the total pressure as lower as possible.

Although it is necessary to be aware that pressure cannot be decreased without verifying how the cycle responses to its alteration. One of the equipments whom functioning could be affected with falling pressure is the condenser. If pressure is too high, the correspondent temperature at the entrance of the condenser will be too low, affecting condensation of butane.

In table 2 pressure was fixed at 4.9 atmospheres and, although it seems a bad value to initialize simulation, it was chosen due to the boiling point of butane. This because with a pressure of 4.9 atmospheres the temperature of stream S1, which contains only butane, will be approximately 50°C, temperature favourable to condensation.

These values can be verified by annex D.

Next altered parameter was the recuperation of butane in the bubble pump. The studied range varies from 90 to 99.9%, also a small variation but the only one in which the cycle could perform correctly with no errors concerning the performance of cycle.

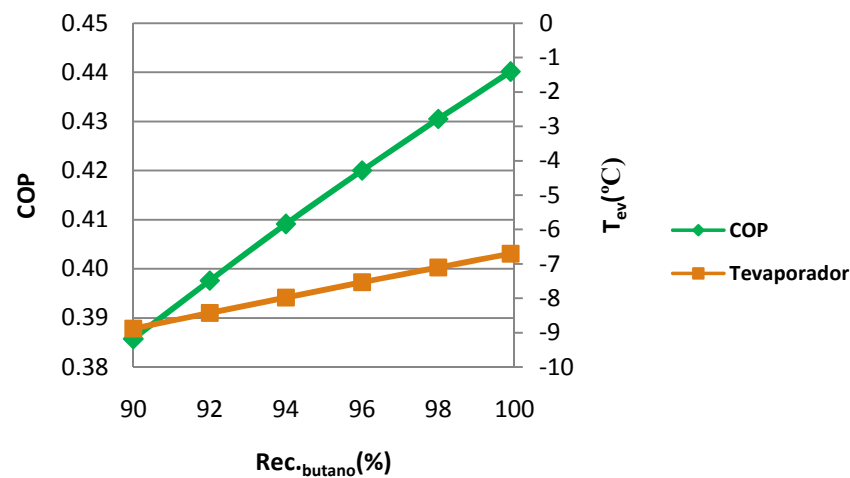


Figure 6 – Recuperation of butane in the bubble pump versus coefficient of performance and outlet temperature of the evaporator

Observing the figure presented above it can be said that increasing the recuperation of butane in the bubble pump reflects also an increment of COP.

Relatively to the temperatures concerning the outlet of the evaporator, once again it can be seen that the conditions are respected. The fact of the temperatures being lower than -5°C , as it was decided, implicates the correct functioning of the evaporator which is cooling down the surrounding environment.

Spite this raise related to the recuperation of butane means a higher percentage of butane working in the whole cycle still, it is necessary to be aware of the other conditions beyond the evaporator temperature. Another fact that must be seen is the temperature from the bottom of the bubble pump which also can contribute to this recuperation.

This topic will be referred in the next figure.

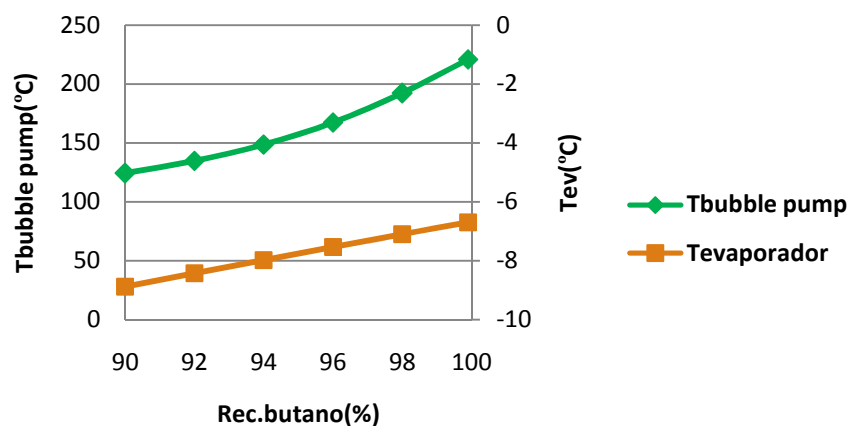


Figure 7 - Butane recuperation in the bubble pump versus temperature from the bottom of the bubble pump and evaporator outlet stream

The construction of this figure was essentially to verify the behaviour of the temperature since temperature cannot be altered in this cycle, being a fixed variable.

Observing the figure above, it can be noticed that the raise concerning the recuperation of butane leaves to a raise of temperature whether in the bubble pump or in the evaporator. But the raise of temperature in the bubble pump its more significant when compared to the raise in the evaporator that only increases in the range of -8.9 to -6.7°C .

Relatively to the bubble pump it is necessary to underline that spite in the bottom of the bubble pump the temperature is increasing with the recuperation of butane, in the top the temperature of the stream 1 remains the same since its composition is composed of pure butane, annex D.

A higher recuperation of butane in the bubble pump implies a higher quantity of butane entering in the evaporator; this will improve refrigeration and, consequently, achieve a higher COP.

Confining now strictly to the evaporator it can be observed that the temperature is raising but still, the COP is improving. This fact may look contradictory with the behaviour observed in figures 5 and 6 but it is not. In figure 7 the recuperation is increasing showing that there is more butane entering in the evaporator and since in the mixture of helium/butane in the evaporator butane is the heavy key then it is normal the raise of temperature. In figures 5 and 6 the temperature of the evaporator raises but there is not more butane entering showing that the raise of temperature without adding butane to the system it cannot be a good sign.

Unfortunately, in annex E it can be observed that the partial debit of butane decrease with the raise of recuperation demonstrating the opposite of what it was said before but this can be explain by the fact that since the expression for the calculation of COP,(1), needs both heat from the bubble pump and evaporator; and since the evaporator was fixed in 1000W, table1, this means that spite altering the composition of butane raising its refrigeration the system will react in a way of maintaining the same power. Because a higher quantity of butane should decrease the needed power in the evaporator but, in spite of everything, this power remains the same.

Another studied parameter was the mass fraction of each component from the mixture used in the cycle. Since it is not possible to change only one of the components without automatically changing the others too it was decided to built 2D and 3D graphics (annex F) to a better visualization relatively to the three components butane, nonane and helium. Two of the graphics are represented below, figure 8 and 9.

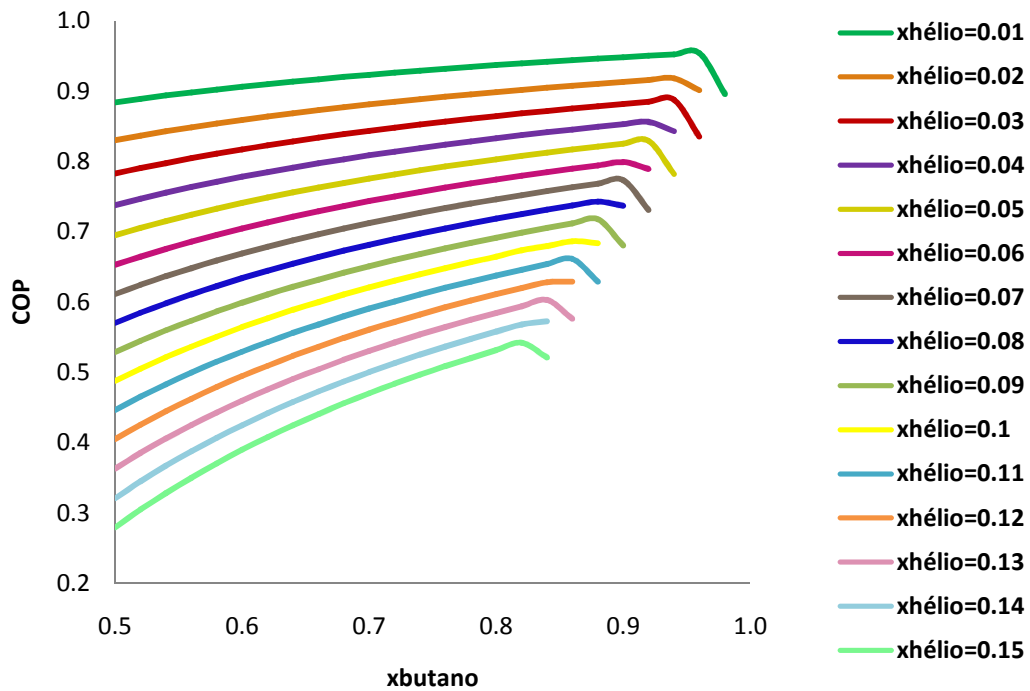


Figure 8 - Mass fraction of butane versus coefficient of performance and considering the mass fraction of helium (2D chart)

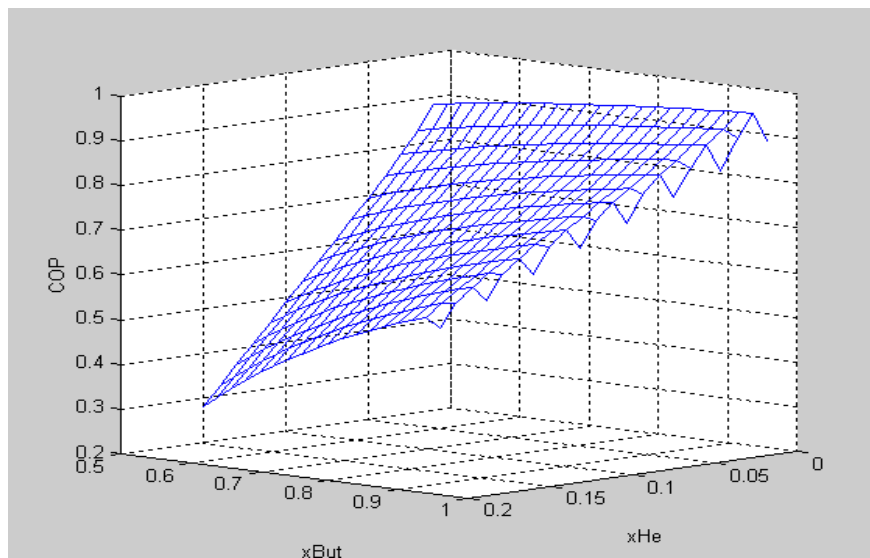


Figure 9 - Mass fraction of butane versus coefficient of performance and considering the mass fraction of helium (3D chart)

Concerning the alterations made for the mass fractions of the mixture from the cycle it can be observed that a maximum was found regarding the value of COP.

The value for the COP maximum is 0.9538 and it is related to low values concerning the mass fraction of helium and higher values for the mass fraction of butane; influence of nonane is not so significant when compared with butane and helium.

Relatively to the cycle representation it can be said that each drawing line corresponds a fixed value for helium altering the other components in a specific range; butane is altered from 0.5 to 0.98 (in its maximum) and nonane is achieved by difference from the two mass fractions varying from 0.01 to 0.49. Helium was modified in a range of 0.01 to 0.15.

Although figure 8 and 9 seem to obtain really good results it is still needed to observe carefully how the cycle behaves with such a higher COP. More characteristics will be shown in the next figure.

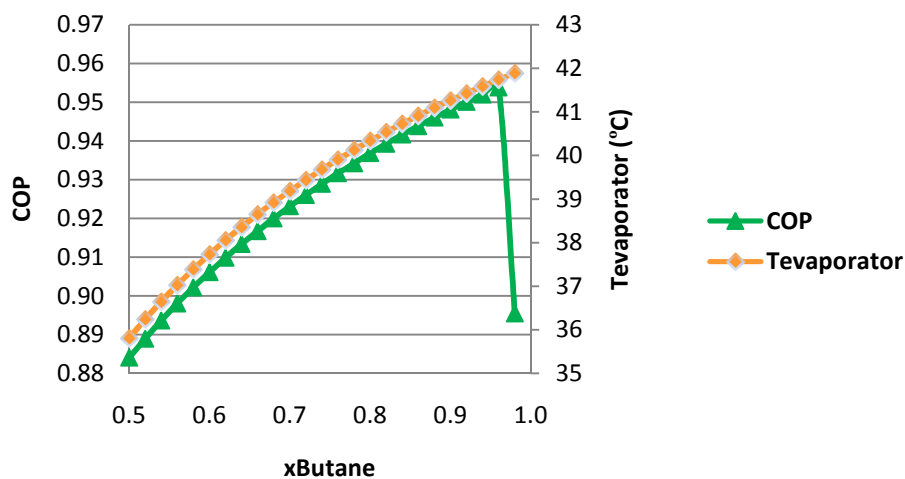


Figure 10 – Mass fraction of butane versus coefficient of performance and outlet temperature of the evaporator

There were several series that could be represented in the figure presented above concerning figure 8 and 9. Although it was decided to limit the anterior range to the serie that presents the highest value for butane and the minimal value for helium due to its behaviour in the previous figure.

The others values are presented in annex H in case of additional data; in this annex it can be seen the correct values which can be applied in the good functioning of the cycle and also which values for COP were obtained by a different estimative concerning the recuperation of the bubble pump.

It can be noticed that observing the temperature of the evaporator to achieve such a higher COP the corresponding temperature must be really high. These high values of temperature for the evaporator show that this device is working as a heater instead of working as a refrigerator, main principle for this study. These values cannot be considered spite of showing the good behaviour between COP and the partial debits.

Although it was permitted to verify how the mass fraction of each component influence COP. Also in this figure it can be confirmed that raising the mass fraction of butane leaves to a higher COP.

It was also decided to compare COP with the temperature from the bottom of the bubble pump, figure 11.

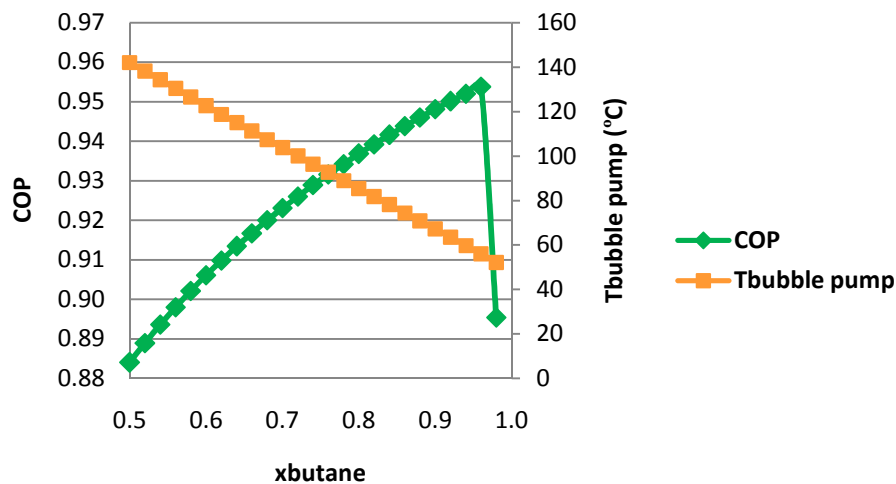


Figure 11 – Mass fraction of butane versus coefficient of performance and temperature from the bottom of the bubble pump

According to this figure when COP increase the temperature from the bubble pump increase achieving 55.97°C for the highest value of COP. This temperature is extremely low for a temperature from the bottom of the bubble pump because to compensate the use of solar energy in the studied cycle the provided temperature to the bubble pump should be nearly 100°C (minimal limit)⁽¹³⁾.

From figure 11 it was confirmed once again that this results cannot be considered.

In the next figure it will be discussed the behaviour of the total flow rate maintaining constant the mass fraction of each component.

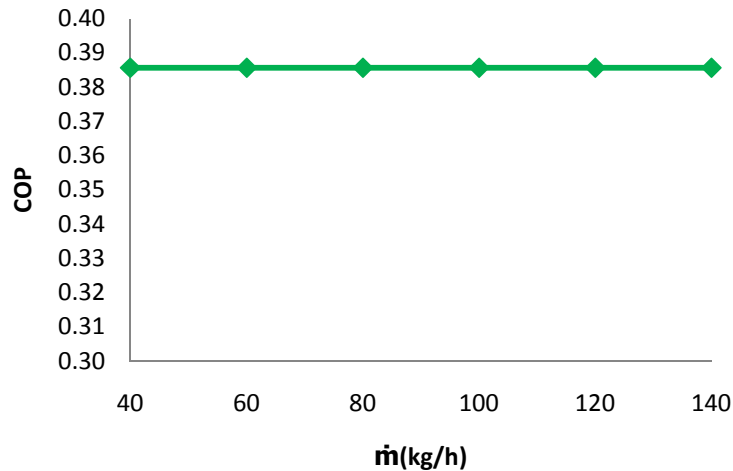


Figure 12 - Total flow rate versus coefficient of performance

This figure is only to certify that COP is not dependent from total flow rate. The alteration of the total flow rate is totally irrelevant for the study of COP, maintaining constant its value of 0.3857.

Spite all the ranges described above being too small concerning its variation it must be notice that it happens due to physical impossibilities relatively to same values outside of the chosen ranges.

This shows that the cycle presents an enormous sensibility concerning the alterations described above.

Although the initial conditions of this cycle were based in documents made by a person who already studied this type of cycles it must be said that since there were used different programs and methods the results are obviously different and they cannot be an example for this project.

In a synthesized way it can be said that COP increase with the:

- Decrease of pressure;
- Increase of recuperation of butane;
- Increase of mass fraction of butane;
- Decrease of mass fraction of helium and nonane.

Relatively to the indirect parameters that were also discussed it can be said that increasing COP leaves to a raise of the evaporator temperature and also a raise of temperature in the bottom of the bubble pump.

Since that the mixture of the bubble pump is a binary mixture composed by nonane (heavy key) and butane (light key) this means that raising temperature from the bottom of the bubble pump the temperature from the top will decrease. This happens because temperature from the bottom will be

approaching the boiling temperature of nonane and on the top it will approach to the butane boiling temperature.

Summarily speaking, the study of the parameters from the DAR cycle permitted to observe the behaviour concerning the COP. Direct or indirectly all the important parameters were verify and criticized. This way it was possible to think about the best estimative in order to proceed with optimization.

3.2.3. Optimization

In order to proceed with optimization there are two important issues that should be referred: the variables that will be optimized as well as the established constraints in the cycle.

The chosen variables for its optimization were the partial debits of nonane, butane and helium together with the outlet temperature of the cycle.

The variables related to the partial debits for being extremely difficult parameters due to its instability and that can easily alter the behaviour of the whole cycle, especially in the evaporator changing the assignment for it was made of – to refrigerate.

The inlet temperature is the other variable but its function is slightly different when compared with the partial debits. This variable was chosen because with the inlet temperature it is possible to verify the equality between the inlet and outlet temperature of the refrigeration cycle, besides this is one of the specified constraints. Since this cycle must be a closed cycle, its construction was made in order to achieve this objective and that is way regarding these two streams are not connected between them they must work like they were the same and that implies having the same conditions.

Relatively to constraints three were defined. The first one concerns to the quantity of power provided to the evaporator which is fixed in 1000W. Another constraint made in order of the same device was the limitation of the outlet stream of the evaporator of -5°C since this is the maximum temperature that the cycle should achieve for efficient refrigeration.

The last constraint, already referred, concerns equality between the inlet and outlet temperature of the cycle. It is mandatory for these two streams to have the same composition.

To notice that pressure also could it be an optimized variable. This variable, together with the others was tested although the response of the cycle concerning pressure could not be applied to this project. The results for pressure were near to 0 and 1 atmospheres, this kind of results cannot be acceptable since the delta respectively to the temperature in the condenser it is too low to permit an efficient condensation. It will be shown an illustrated figure in order to a better understanding about this subject.

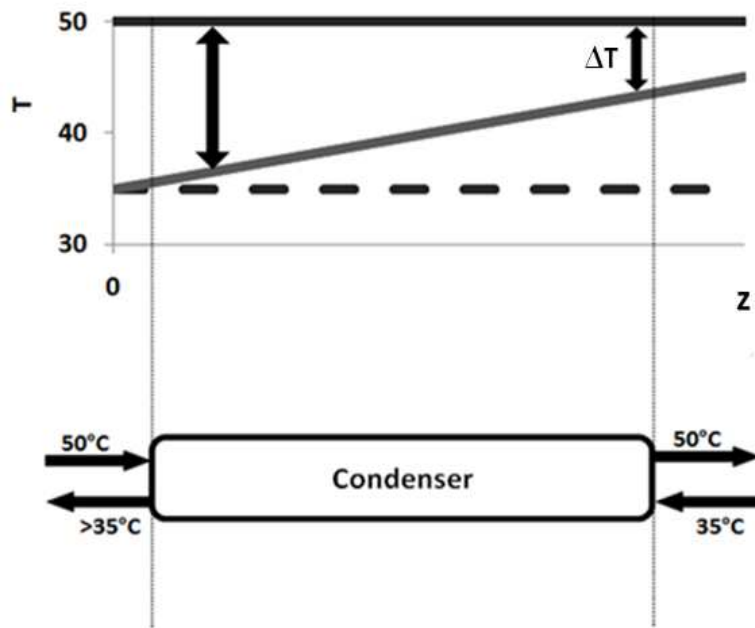


Figure 13 - Relation between temperature and length of the condenser

Concerning this figure it can be explained the relation between the temperature and length of the condenser.

In this figure it was assumed that the chosen fluid to condense butane was air, reason why the limit concerning the lower temperature is 35°C.

The length of the condenser depends from the ΔT , difference between the temperature of the working fluid butane and from the external source air. The range for air is between 12 to 15°C as it was said before.

If water was the chosen fluid the difference between these temperatures should be around 5°C.

It is logical that an inferior delta, that is not included in the determined range, will increase the length of the condenser. This happens because it is needed a higher area to establish the exchange of heat that is required.

This explanation can also be verified by the expression,

$$Q = U.A.\Delta T \quad (2)$$

So, it was demonstrated that a delta out of the referred ranges can be prejudicial regarding the profit of this project.

That way, spite not optimizing pressure it must be aware that it was decided to manually change this parameter we must pay attention to the condenser.

The beginning of optimization started with a manual estimative for pressure maintaining the initial estimative relatively to the other parameters in order to see which the best value to fix pressure was. After, the inlet temperature was studied in order to make a better approach and then, it was tried to change estimative of the mass fractions for the three components. The results permitted to achieve a higher COP and also obtain trustable values for the other parameters.

Table 3 - Initial estimative and its results for the first optimization

Initial Estimative	
x_{Helium}	0.13
x_{Nonane}	0.35
x_{Butane}	0.52
P(atm)	4.50
$T_{\text{inlet}} \text{ (K)}$	319.15
Results	
x_{Helium}	0.13
x_{Nonane}	0.21
x_{Butane}	0.66
COP	-0.539
$T_{\text{inlet}} \text{ (K)}$	287.07
$T_{\text{outlet}} \text{ (K)}$	287.35

Table 4 - Initial estimative and its results for the second optimization

Initial Estimative	
x_{Helium}	0.13
x_{Nonane}	0.35
x_{Butane}	0.52
P(atm)	4.50
$T_{\text{inlet}} \text{ (K)}$	322.15
Results	
x_{Helium}	0.13
x_{Nonane}	0.19
x_{Butane}	0.68
COP	-0.540
$T_{\text{inlet}} \text{ (K)}$	285.87
$T_{\text{outlet}} \text{ (K)}$	286.15

Table 5 - Initial estimative and its results for the third optimization

Initial Estimative	
x_{Helium}	0.13
x_{Nonane}	0.27
x_{Butane}	0.60
P(atm)	4.50
T_{inlet} (K)	322.15
Results	
x_{Helium}	0.13
x_{Nonane}	0.18
x_{Butane}	0.69
COP	-0.541
T_{inlet} (K)	285.09
T_{outlet} (K)	285.37

Table 6 - Initial estimative and its results for the fourth optimization

Initial Estimative	
x_{Helium}	0.09
x_{Nonane}	0.27
x_{Butane}	0.64
P(atm)	4.50
T_{inlet} (K)	322.15
Results	
x_{Helium}	0.13
x_{Nonane}	0.2
x_{Butane}	0.67
COP	-0.539
T_{inlet} (K)	286.23
T_{outlet} (K)	286.23

The related results with the four optimizations represented above were considered acceptable due to the fact of respecting all the needed conditions for the studied cycle.

Most part of the results concerning optimization could never be applied to the cycle. Having a partial debit equal to zero of one of the components or even a positive COP (indicating that the balances due to the evaporator or the bubble pump were not being correctly done) are some of the examples.

To notice that optimization was made in order to minimize the heat from the bubble pump, reason why appears in the negative form.

From the results presented above the best obtained COP was of -0.541, table 5.

Since that the pressure corresponding to this COP is lower than 4.9 atmospheres it was necessary to verify the difference of temperatures between the condenser and air.

The stream of the entrance of the bubble pump, stream S1, has a temperature of 47°C which means that the obtained ΔT is equal to 12°C. This value is inside the established range for air which means that is also respecting the range for water.

The same values presented in tables 3, 4, 5 and 6 were also optimized for a 4.9 atmospheres pressure. All the other conditions concerning the initial estimative were maintained. The objective here is to verify, once again, the impact that his alteration in total pressure provoke in the cycle and to compare the values achieved for the two considered pressures.

Table 7 - Results for both pressures concerning the initial estimative presented in table 3

Results			
P=4.5 atm		P=4.9 atm	
x_{Helium}	0.13	x_{Helium}	0.13
x_{Nonane}	0.21	x_{Nonane}	0.21
x_{Butane}	0.66	x_{Butane}	0.66
COP	-0.539	COP	-0.482
$T_{\text{inlet}} \text{ (K)}$	287.07	$T_{\text{inlet}} \text{ (K)}$	286.40
$T_{\text{outlet}} \text{ (K)}$	287.35	$T_{\text{outlet}} \text{ (K)}$	286.40

Table 8 - results for both pressures concerning the initial estimative presented in table 4

Results			
P=4.5 atm		P=4.9 atm	
x_{Helium}	0.13	x_{Helium}	0.09
x_{Nonane}	0.19	x_{Nonane}	0.46
x_{Butane}	0.68	x_{Butane}	0.45
COP	-0.540	COP	-0.468
$T_{\text{inlet}} \text{ (K)}$	285.87	$T_{\text{inlet}} \text{ (K)}$	301.67
$T_{\text{outlet}} \text{ (K)}$	286.15	$T_{\text{outlet}} \text{ (K)}$	301.97

Table 9 - Results for both pressures concerning the initial estimative presented in table 6

Results			
P=4.5 atm		P=4.9 atm	
x_{Helium}	0.13	x_{Helium}	0.14
x_{Nonane}	0.20	x_{Nonane}	0.18
x_{Butane}	0.67	x_{Butane}	0.68
COP	-0.539	COP	-0.483
T_{inlet} (K)	286.227	T_{inlet} (K)	284.86
T_{outlet} (K)	286.227	T_{outlet} (K)	284.86

From tables 7, 8 and 9 it can be observed that the values related to the pressure of 4.9 atmospheres have lower values for COP when compared to 4.5 atmospheres pressure. This comparison permitted to verify once again that the 4.5 atmospheres pressure is the better estimative considering this cycle.

Other points that should be also referred are related with the results given for both pressures. In table 8 the results concerning the pressure of 4.9 atmospheres showed more nonane than butane which cannot be right since butane is the refrigerant and needs to be present in a higher quantity. The best value obtained for this optimization, COP=-0.541, is not here referred for the pressure of 4.9 atmospheres due to an error with the optimization. The program could not perform the optimization for the 4.9 atmospheres maintaining the three wanted constraints.

In state of art it was presented some studies related to the evolution of this cycle during the years, sub-chapter 2.2. In a way to establish a comparison regarding this evolution, these values were compiled to be compared with the present study.

Table 10 - Comparison between the coefficients of performance

COP			
Present Study	Chen et al.	Srikhirin and Aphornratana	Zohar et al.
-0.541	0.1-0.2	0.09-0.15	0.15

It can be observed that the COP obtained in the present study has a significant value when compared with the other studies, some of them made only a few years ago.

To be noticed that all the names referred above made an investigation in the DAR cycles area and the achieved COP were calculated by the same way showing that this values can be compared between them.

So, spite not having a value as good as if it was performed with a solution of ammonia, water and hydrogen (COP=2.03⁽¹⁶⁾) or not achieving the results in a range of 2 to 6 for COP like in the compression cycles this project could be promising and with no impact to the environment.

Although several considerations were made in this investigation, it is a fact that with the right tools and expanding research on this area these types of cycles could be easily improved and applied in the future.

4. Conclusion

A diffusion-absorption refrigeration (DAR) cycle operates by thermal energy and is known for its silent operation, durability and minimal maintenance costs. Unfortunately is still also known by its lower coefficient of performance (COP).

The mixture used in the DAR cycle is composed by nonane and butane as the working fluids; together with the auxiliary inert gas helium. The main purpose of this mixture is reducing the environmental impact at the same time that also can achieve a high performance in the cycle.

Several equations of state were tested for this cycle with only two presenting good results relatively to the good functioning of the cycle: Soave-Redlich-Kwong (SRK) and Peng-Robinson (PR) equation of state. Spite SRK presents a better COP, PR was chosen due to its best integration with the conditions of the cycle since is the best equation of state indicated to work with condensable fluids.

Concerning the studied parameters regarding its influence to the COP it can be said that spite its behaviour it should be looked for its middle terms respecting all the conditions of the cycle.

The raise of pressure leaves the COP to decrease. Temperature of the evaporator also rises with pressure, which is a bad sign concerning the feasibility of the cycle since the quantity of butane on the entrance of the evaporator is a fix variable at this point.

Relatively to the recuperation of butane in the bubble pump it can be said that the raise of recuperation means a higher COP. Both temperatures for the evaporator and bubble pump rise too. This behaviour could be explained by the fact that in the bubble pump more power should be provided to achieve such a higher recuperation so, in the bottom of the bubble pump temperature will be higher. In the evaporator since there is more quantity of butane at the entrance this will make the temperature of the solution helium/butane increase.

It was also changed the mass fraction of butane, nonane and helium. The decrease of helium and nonane leaves to a higher COP. Raising butane, since is the refrigerant, means higher refrigeration and, consequently, a higher COP. Unfortunately the studied range for the mass fractions leaves also to a higher temperature of the evaporator, turning this device into a heater instead of a refrigerator.

Relatively to the total flow rate it can be said that its alteration is irrelevant to COP showing a constant behaviour.

Concerning optimization the best achieved value for COP was -0.541 respecting all the conditions of the DAR cycle. As one of the parameters it was decided to alter pressure from 4.9 to 4.5 atmospheres showing a remarkable improvement for COP in this small interval. To add that with

this pressure the condition in the condenser concerning the deltas of the established ranges for water and air were respected.

This means that with the right tools and an expansion concerning the investigation on this area this project can be viable.

5. Work Assessment

5.1. Aims achieved

This project objective consisted in a simulation and numerical optimization of a diffusion-absorption refrigeration (DAR) cycle powered by solar energy. The refrigeration mixture of this cycle was composed by the working fluids butane and nonane together with helium as the inert gas.

The simulation was executed in a way to obtain the most adequate variables to optimize the cycle. Respecting simulation the proposed objectives were achieved and the results were presented above.

Optimization also permitted to achieve results although more time was needed to execute more tests and, probably, to found a better COP.

5.2 Limitations and further work

The most important limitation to be referred about this project is related to the time for developing this thesis. I believe that this time is too short to obtain any kind of results considered as valid ones.

The fact of being only five months limits the number of tests as well as affects putting in practice new ideas that could result in this project improvement.

Having more time had resulted in a deeper knowledge related with the study of the parameters and its behaviour as well as it would allowed to calculate the interaction parameters specific for this mixture achieving more real results and with less considerations made during this project. Pressure could it be an optimized variable but with associated constraints. The cycle should be constructed with an absorber provided with an appropriated number of floors in order to achieve a good absorption. All of these referred points could be new objectives for a future work.

5.3. Final appreciation

Realizing this project in a foreign institution and in a foreign country allowed me to achieve a higher independency as well as a bigger autonomy concerning this project and also my life.

Working on this thesis permitted me to test my know-how and my initiative in several moments.

The fact of working on a thesis that involved computational simulation and optimization, fact that I have never thought about it until now, allowed me to acquire a higher knowledge in this area, area that I consider of extremely interest. Unfortunately, spite all my efforts; there was not enough time to realize everything that I wanted to.

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Appendix A – Streams data concerning Peng-Robinson and Soave-Redlich-Kwong equations of state

	Peng-Robinson			Soave-Redlich-Kwong		
inlet stream	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	18.1191	57.0318	4.9	18.7435	54.2628
	Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.9611		n-nonane	18.992	
	n-butane	29.6566		n-butane	28.2166	
helium	7.41414		helium	7.05416		
	Physical State			Physical State		
	liquid,vapour			liquid,vapour		
stream S1	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	50.0946	26.6909	4.9	49.722	25.395
	Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0	
	n-butane	26.6909		n-butane	25.395	
helium	0		helium	0		
	Physical State			Physical State		
	vapour			vapour		
stream S2	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	50.0946	26.6909	4.9	49.722	25.395
	Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0	
	n-butane	26.6909		n-butane	25.395	
helium	0		helium	0		
	Physical State			Physical State		
	liquid			liquid		
stream S3	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	-8.88886	34.105	4.9	-8.33502	32.4491
	Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0	
	n-butane	26.6909		n-butane	25.395	
helium	7.41414		helium	7.05416		
	Physical State			Physical State		
	vapour			vapour		

stream S4	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	50	49.6177	4.9	50	47.2086
	Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.9611		n-nonane	18.992	
	n-butane	29.6566		n-butane	28.2166	
	helium	0		helium	0	
	Physical State			Physical State		
	liquid			liquid		

stream S5	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	64.8779	49.6177	4.9	64.4359	47.2086
	Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.9611		n-nonane	18.992	
	n-butane	29.6566		n-butane	28.2166	
	helium	0		helium	0	
	Physical State			Physical State		
	liquid,vapour			liquid,vapour		

stream S6	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	124.239	22.9268	4.9	123.611	21.8136
	Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.9611		n-nonane	18.992	
	n-butane	2.96566		n-butane	2.82166	
	helium	0		helium	0	
	Physical State			Physical State		
	liquid			liquid		

stream S7	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	55	22.9268	4.9	55	21.8136
	Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.9611		n-nonane	18.992	
	n-butane	2.96566		n-butane	2.82166	
	helium	0		helium	0	
	Physical State			Physical State		
	liquid			liquid		

stream S8	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	50	7.41414	4.9	50	7.05416
	Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0	
	n-butane	0		n-butane	0	
	helium	7.41414		helium	7.05416	
	Physical State			Physical State		
	vapour			vapour		

stream Sxx	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	-15.814	34.105	4.9	-15.4335	32.4491
	Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0	
	n-butane	26.6909		n-butane	25.395	
	helium	7.41414		helium	7.05416	
	Physical State			Physical State		
	liquid,vapour			liquid,vapour		

outlet	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	18.1191	57.0318	4.9	18.7435	54.2628
	Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.9611		n-nonane	18.992	
	n-butane	29.6566		n-butane	28.2166	
	helium	7.41414		helium	7.05416	
	Physical State			Physical State		
	liquid,vapour			liquid,vapour		

Appendix B – Peng-Robinson equation of state

The EOS used to for the studied cycle, Peng-Robinson, is represented below,

$$P = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)+b(V-b)} \quad (\text{B1})$$

Where,

$$a = \frac{0.45724R^2T_c^2}{P_c} \left[1 + m(1 - \sqrt{T_r}) \right]^2 \quad (\text{B2})$$

$$m = 0.37464 + 1.54226\omega - 0.26992\omega^2 \quad (\text{B3})$$

$$b = \frac{0.0778RT_c}{P_c} \quad (\text{B4})$$

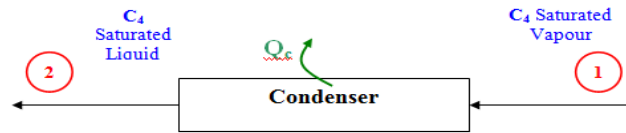
This cubic equation, (A1), has two members: the first one represents the repulsive forces between molecules and the second corresponds to the attractive term where a, the energetic parameter, measure the intermolecular attraction forces and is strongly dependent from the temperature.

Peng-Robinson state equation is often used for industrial calculation due to its analytical resolution and experimental results reproduction for simple fluids.

A single equation of state (EOS), such as Peng-Robinson EOS, can accurately describe both liquid and vapour phase.

Appendix C – Conservation equations

The mass and energy balance equations for the various elements of the system are represented below. The equipment is illustrated as well as its stream characteristics.



General mass balance

$$V_1 = L_2 \quad (C1)$$

Partial mass balance

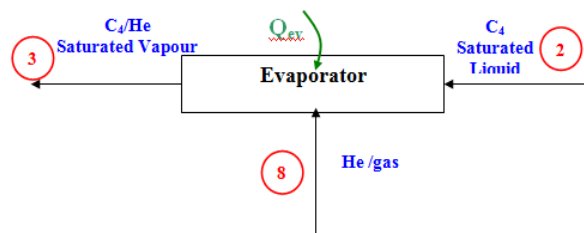
$$y_1 = x_2 = 1 \quad (C2)$$

Energetic balance

$$V_1 H_1^{Sat.Vap.}(T_1) + Q_c = L_2 H_2^{Sat.Liq.}(T_2)$$

From the expressions (3) and (6) showed above,

$$V_1 [H_{C_4}^{Sat.Vap.}(T_1) - H_{C_4}^{Sat.Liq.}(T_1)] = -Q_c \quad (C3)$$



General mass balance

$$L_2 + V_8 = V_3 \Rightarrow V_1 + V_8 = V_3 \quad (C4)$$

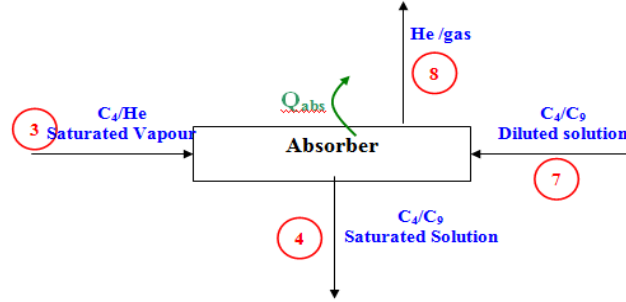
Partial mass balance

$$L_2 = y_3 \cdot V_3 \Rightarrow V_1 = y_3 \cdot V_3 \quad (C5)$$

Energetic balance

$$L_2 H_2^{Sat.Liq.}(T_2) + V_8 H_{He}(T_8) + Q_{ev} = V_3 [y_3 H_{C_4}^{Sat.Vap.}(T_3) + (1 - y_3) H_{He}(T_3)] \Leftrightarrow$$

$$V_1 H_2^{Sat.Liq.}(T_1) + V_8 H_{He}(T_8) + Q_{ev} = V_3 [y_3 H_{C_4}^{Sat.Vap.}(T_3) + (1 - y_3) H_{He}(T_3)] \quad (C6)$$



General mass balance

$$V_3 + L_7 = L_4 + V_8 \quad (C7)$$

Partial mass balance

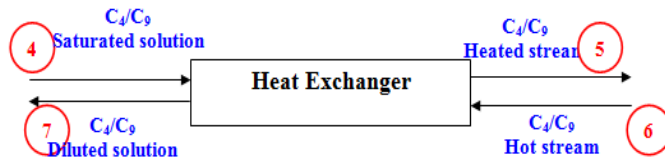
$$y_3 \cdot V_3 + x_7 \cdot L_7 = x_4 \cdot L_4 \quad (C8)$$

Energetic balance

$$V_3 H_3 + L_7 H_7 = L_4 H_4 + V_8 H_8 - Q_{abs} \Leftrightarrow V_3 [y_3 H_{C_4}^{Sat.Vap.}(T_3) + (1 - y_3) H_{He}(T_3)] +$$

$$L_7 [x_7 H_{C_4}^{Sat.Liq.}(T_7) + (1 - x_7) H_{C_9}^{Sat.Liq.}(T_7)] = L_4 [x_4 H_{C_4}^{Sat.Liq.}(T_4) + (1 - x_4) H_{C_9}^{Sat.Liq.}(T_4)] +$$

$$V_8 H_{He}(T_8) - Q_{abs} \quad (C9)$$



General mass balance

$$L_5 = L_4 \quad (C10)$$

$$L_6 = L_7 \quad (C11)$$

Partial mass balance

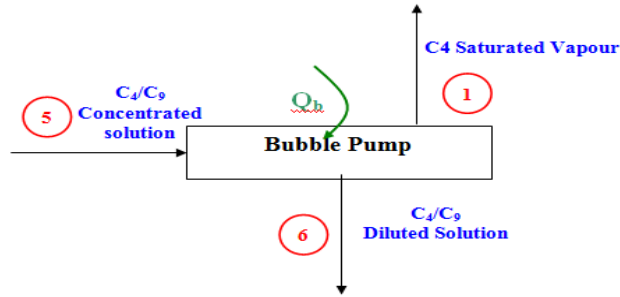
$$x_5 = x_4 \quad (C12)$$

$$x_6 = x_7 \quad (C13)$$

Energetic balance

$$L_4 H_4 + L_6 H_6 = L_5 H_5 + L_7 H_7 \Leftrightarrow L_4 H_4 + L_7 H_6 = L_4 H_5 + L_7 H_7$$

$$\begin{aligned} & L_4 [x_4 H_{C_4}^{Sat.Liq.}(T_4) + (1-x_4) H_{C_9}^{Sat.Liq.}(T_4)] + L_7 [x_6 H_{C_4}^{Sat.Liq.}(T_6) + (1-x_6) H_{C_9}^{Sat.Liq.}(T_6)] = \\ & L_4 [x_5 H_{C_4}^{Sat.Liq.}(T_5) + (1-x_5) H_{C_9}^{Sat.Liq.}(T_5)] + L_7 [x_7 H_{C_4}^{Sat.Liq.}(T_7) + (1-x_7) H_{C_9}^{Sat.Liq.}(T_7)] \Leftrightarrow \\ & L_4 [x_4 H_{C_4}^{Sat.Liq.}(T_4) + (1-x_4) H_{C_9}^{Sat.Liq.}(T_4)] + L_7 [x_7 H_{C_4}^{Sat.Liq.}(T_6) + (1-x_7) H_{C_9}^{Sat.Liq.}(T_6)] = \\ & L_4 [x_4 H_{C_4}^{Sat.Liq.}(T_5) + (1-x_4) H_{C_9}^{Sat.Liq.}(T_5)] + L_7 [x_7 H_{C_4}^{Sat.Liq.}(T_7) + (1-x_7) H_{C_9}^{Sat.Liq.}(T_7)] \end{aligned} \quad (C14)$$



General mass balance

$$L_5 = L_6 + V_1 \quad (C15)$$

Partial mass balance

$$x_5 \cdot L_5 = x_6 \cdot L_6 + V_1 \quad (C16)$$

Energetic balance

$$\begin{aligned} & L_5 H_5 + Q_B = V_1 H_1 + L_6 H_6 \Leftrightarrow L_4 H_5 + Q_B = V_1 H_1 + L_7 H_6 \Leftrightarrow \\ & L_4 [x_4 H_{C_4}^{Sat.Liq.}(T_5) + (1-x_4) H_{C_9}^{Sat.Liq.}(T_5)] + Q_B = V_1 H_{C_4}^{Sat.Vap.}(T_1) + \\ & L_7 [x_7 H_{C_4}^{Sat.Liq.}(T_6) + (1-x_7) H_{C_9}^{Sat.Liq.}(T_6)] \end{aligned} \quad (C17)$$

Appendix D – Streams data concerning the pressure variance

Stream	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
inlet stream	4	14.1698	55.1385	4.2	15.1084	55.543	4.4	16.0097	55.9569
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.2985		n-nonane	19.4401		n-nonane	19.5849	
	n-butane	28.672		n-butane	28.8824		n-butane	29.0976	
helium	7.16801		helium	7.22059		helium	7.2744		
Physical State			Physical State			Physical State			
liquid,vapour			liquid,vapour			liquid,vapour			
stream S1	4	42.5286	25.8048	4.2	44.3134	25.9941	4.4	46.0351	26.1878
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
	n-butane	25.8048		n-butane	25.9941		n-butane	26.1878	
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
vapour			vapour			vapour			
stream S2	4	42.5286	25.8048	4.2	44.3134	25.9941	4.4	46.0351	26.1878
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
	n-butane	25.8048		n-butane	25.9941		n-butane	26.1878	
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid			liquid			liquid			
stream S3	4	-13.5446	32.9728	4.2	-12.4385	33.2147	4.4	-11.376	33.4622
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
	n-butane	25.8048		n-butane	25.9941		n-butane	26.1878	
helium	7.16801		helium	7.22059		helium	7.2744		
Physical State			Physical State			Physical State			
vapour			vapour			vapour			

stream S4	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4	50	47.9705	4.2	50	48.3224	4.4	50	48.6825
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.2985		n-nonane	19.4401		n-nonane	19.5849	
n-butane	28.672		n-butane	28.8824		n-butane	29.0976		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid			liquid			liquid			

stream S5	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4	56.6595	47.9705	4.2	58.5945	48.3224	4.4	60.4633	48.6825
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.2985		n-nonane	19.4401		n-nonane	19.5849	
n-butane	28.672		n-butane	28.8824		n-butane	29.0976		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid,vapour			liquid,vapour			liquid,vapour			

stream S6	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4	111.738	22.1657	4.2	114.665	22.3283	4.4	117.501	22.4947
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.2985		n-nonane	19.4401		n-nonane	19.5849	
n-butane	2.8672		n-butane	2.88824		n-butane	2.90976		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid			liquid			liquid			

stream S7	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4	55	22.1657	4.2	55	22.3283	4.4	55	22.4947
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.2985		n-nonane	19.4401		n-nonane	19.5849	
n-butane	2.8672		n-butane	2.88824		n-butane	2.90976		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid			liquid			liquid			

stream S8	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4	50	7.16801	4.2	50	7.22059	4.4	50	7.2744
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
n-butane	0		n-butane	0		n-butane	0		
helium	7.16801		helium	7.22059		helium	7.2744		
Physical State			Physical State			Physical State			
vapour			vapour			vapour			
stream Sxx	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4	-20.4496	32.9728	4.2	-19.3539	33.2147	4.4	-18.2983	33.4622
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
n-butane	25.8048		n-butane	25.9941		n-butane	26.1878		
helium	7.16801		helium	7.22059		helium	7.2744		
Physical State			Physical State			Physical State			
liquid,vapour			liquid,vapour			liquid,vapour			
outlet	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4	14.1698	55.1385	4.2	15.1084	55.543	4.4	16.0097	55.9569
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.2985		n-nonane	19.4401		n-nonane	19.5849	
n-butane	28.672		n-butane	28.8824		n-butane	29.0976		
helium	7.16801		helium	7.22059		helium	7.2744		
Physical State			Physical State			Physical State			
liquid,vapour			liquid,vapour			liquid,vapour			
inlet stream	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.6	16.8769	56.38	4.8	17.7124	56.8123	5	18.5187	57.2537
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.733		n-nonane	19.8843		n-nonane	20.0388	
n-butane	29.3176		n-butane	29.5424		n-butane	29.7719		
helium	7.3294		helium	7.5836		helium	7.44298		
Physical State			Physical State			Physical State			
liquid,vapour			liquid,vapour			liquid,vapour			

stream S1	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.6	47.6987	26.3858	4.8	49.3085	26.5881	5	50.8686	26.7947
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
n-butane	26.3858		n-butane	26.5881		n-butane	26.7947		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
vapour			vapour			vapour			

stream S2	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.6	47.6987	26.3858	4.8	49.3085	26.5881	5	50.8686	26.7947
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
n-butane	26.3858		n-butane	26.5881		n-butane	26.7947		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid			liquid			liquid			

stream S3	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.6	-10.3537	33.7152	4.8	-9.36848	33.9737	5	-8.41749	34.2377
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
n-butane	26.3858		n-butane	26.5881		n-butane	26.7947		
helium	7.3294		helium	7.3856		helium	7.44298		
Physical State			Physical State			Physical State			
vapour			vapour			vapour			

stream S4	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.6	50	49.0506	4.8	50	49.4267	5	50	49.8107
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.733		n-nonane	19.8843		n-nonane	20.0388	
n-butane	29.3176		n-butane	29.5424		n-butane	29.7719		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid			liquid			liquid			

stream S5	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.6	62.2709	49.0506	4.8	64.0221	51.0818	5	65.7211	49.8107
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.733		n-nonane	19.8843		n-nonane	20.0388	
	n-butane	29.3176		n-butane	29.5424		n-butane	29.7719	
	helium	0		helium	0		helium	0	
	Physical State			Physical State			Physical State		
	liquid,vapour			liquid,vapour			liquid,vapour		

stream S6	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.6	120.254	22.6648	4.8	122.929	22.8385	5	125.532	23.016
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.733		n-nonane	19.8843		n-nonane	20.0388	
	n-butane	2.93176		n-butane	2.95424		n-butane	2.97719	
	helium	0		helium	0		helium	0	
	Physical State			Physical State			Physical State		
	liquid			liquid			liquid		

stream S7	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.6	55	22.6648	4.8	55	22.8385	5	55	23.016
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.733		n-nonane	19.8843		n-nonane	20.0388	
	n-butane	2.93176		n-butane	2.95424		n-butane	2.97719	
	helium	0		helium	0		helium	0	
	Physical State			Physical State			Physical State		
	liquid			liquid			liquid		

stream S8	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.6	50	7.3294	4.8	50	7.3856	5	50	7.44298
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
	n-butane	0		n-butane	0		n-butane	0	
	helium	7.3294		helium	7.3856		helium	7.44298	
	Physical State			Physical State			Physical State		
	vapour			vapour			vapour		

stream Sxx	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.6	-17.2794	33.7152	4.8	-16.2945	33.9737	5	-15.341	34.2377
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
	n-butane	26.3858		n-butane	26.5881		n-butane	26.7947	
	helium	7.3294		helium	7.3856		helium	7.44298	
	Physical State			Physical State			Physical State		
	liquid,vapour			liquid,vapour			liquid,vapour		

outlet	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.6	16.8769	56.38	4.8	17.7124	56.8123	5	18.5187	57.2537
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.733		n-nonane	19.8843		n-nonane	20.0388	
	n-butane	29.3176		n-butane	29.5424		n-butane	29.7719	
	helium	7.3294		helium	7.3856		helium	7.44298	
	Physical State			Physical State			Physical State		
	liquid,vapour			liquid,vapour			liquid,vapour		

inlet stream	P(atm)	T(°C)	Q(kg/h)
	5.2	19.2977	57.7042
	Partial Debits (kg/h)		
	n-nonane	20.1965	
	n-butane	30.0062	
	helium	7.50155	
	Physical State		
	liquid,vapour		

stream S1	P(atm)	T(°C)	Q(kg/h)
	5.2	52.3824	27.0056
	Partial Debits (kg/h)		
	n-nonane	0	
	n-butane	27.0056	
	helium	0	
	Physical State		
	vapour		

stream S2	P(atm)	T(°C)	Q(kg/h)
	5.2	52.3824	27.0056
Partial Debits (kg/h)			
n-nonane	0		
n-butane	27.0056		
helium	0		
Physical State			
liquid			

stream S3	P(atm)	T(°C)	Q(kg/h)
	5.2	-7.49834	34.5071
Partial Debits (kg/h)			
n-nonane	0		
n-butane	27.0056		
helium	7.50155		
Physical State			
vapour			

stream S4	P(atm)	T(°C)	Q(kg/h)
	5.2	50	50.2027
Partial Debits (kg/h)			
n-nonane	20.1965		
n-butane	30.0062		
helium	0		
Physical State			
liquid			

stream S5	P(atm)	T(°C)	Q(kg/h)
	5.2	67.3713	50.2027
Partial Debits (kg/h)			
n-nonane	20.1965		
n-butane	30.0062		
helium	0		
Physical State			
liquid,vapour			

stream S6	P(atm)	T(°C)	Q(kg/h)
	5.2	128.068	23.1971
Partial Debits (kg/h)			
n-nonane	20.1965		
n-butane	3.00062		
helium	0		
Physical State			
liquid			

stream S7	P(atm)	T(°C)	Q(kg/h)
	5.2	55	23.1971
Partial Debits (kg/h)			
n-nonane	20.1965		
n-butane	3.00062		
helium	0		
Physical State			
liquid			

stream S8	P(atm)	T(°C)	Q(kg/h)
	5.2	50	7.50155
Partial Debits (kg/h)			
n-nonane	0		
n-butane	0		
helium	7.50155		
Physical State			
vapour			

stream Sxx	P(atm)	T(°C)	Q(kg/h)
	5.2	-14.4166	34.5071
Partial Debits (kg/h)			
n-nonane	0		
n-butane	27.0056		
helium	7.50155		
Physical State			
liquid,vapour			

outlet	P(atm)	T(°C)	Q(kg/h)
	5.2	19.2977	57.7042
Partial Debits (kg/h)			
n-nonane		20.1965	
n-butane		30.0062	
helium		7.50155	
Physical State			
		liquid,vapour	

Appendix E – Streams data concerning the recuperation of butane

	xbutano=0.9			xbutano=0.92			xbutano=0.94		
inlet stream	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	18.1191	57.0318	4.9	18.9434	54.1884	4.9	19.7768	51.616
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.9611		n-nonane	18.9659		n-nonane	18.0656	
n-butane	29.6566		n-butane	28.178		n-butane	26.8403		
helium	7.41414		helium	7.04449		helium	6.71008		
	Physical State			Physical State			Physical State		
	liquid,vapour			liquid,vapour			liquid,vapour		
stream S1	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	50.0946	26.6909	4.9	50.0946	25.9237	4.9	50.0946	25.2299
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
n-butane	26.6909		n-butane	25.9237		n-butane	25.2299		
helium	0		helium	0		helium	0		
	Physical State			Physical State			Physical State		
	vapour			vapour			vapour		
stream S2	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	50.0946	26.6909	4.9	50.0946	25.9237	4.9	50.0946	25.2299
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
n-butane	26.6909		n-butane	25.9237		n-butane	25.2299		
helium	0		helium	0		helium	0		
	Physical State			Physical State			Physical State		
	liquid			liquid			liquid		
stream S3	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	-8.88886	34.105	4.9	-8.42881	32.9682	4.9	-7.97846	31.94
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
n-butane	26.6909		n-butane	25.9237		n-butane	25.2299		
helium	7.41414		helium	7.04449		helium	6.71008		
	Physical State			Physical State			Physical State		
	vapour			vapour			vapour		

stream S4	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	50	49.6177	4.9	50	47.1439	4.9	50	44.9059
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.9611		n-nonane	18.9659		n-nonane	18.0656	
n-butane	29.6566		n-butane	28.178		n-butane	26.8403		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid			liquid			liquid			

stream S5	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	64.8779	49.6177	4.9	65.6118	47.1439	4.9	66.7022	44.9059
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.9611		n-nonane	18.9659		n-nonane	18.0656	
n-butane	29.6566		n-butane	28.178		n-butane	26.8403		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid,vapour			liquid,vapour			liquid,vapour			

stream S6	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	124.239	22.9268	4.9	134.471	21.2202	4.9	148.633	19.676
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.9611		n-nonane	18.9659		n-nonane	18.0656	
n-butane	2.96566		n-butane	2.25424		n-butane	1.61042		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid			liquid			liquid			

stream S7	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	55	22.9268	4.9	55	21.2202	4.9	55	19.676
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	19.9611		n-nonane	18.9659		n-nonane	18.0656	
n-butane	2.96566		n-butane	2.25424		n-butane	1.61042		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid			liquid			liquid			

stream S8	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	50	7.41414	4.9	50	7.04449	4.9	50	6.71008
Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)			
n-nonane	0		n-nonane	0		n-nonane	0		
n-butane	0		n-butane	0		n-butane	0		
helium	7.41414		helium	7.04449		helium	6.71008		
Physical State			Physical State			Physical State			
vapour			vapour			vapour			

stream Sxx	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	-15.814	34.105	4.9	-15.614	32.9682	4.9	-15.4165	31.94
Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)			
n-nonane	0		n-nonane	0		n-nonane	0		
n-butane	26.6909		n-butane	25.9237		n-butane	25.2299		
helium	7.41414		helium	7.04449		helium	6.71008		
Physical State			Physical State			Physical State			
liquid,vapour			liquid,vapour			liquid,vapour			

outlet	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	18.1191	57.0318	4.9	18.9434	54.1884	4.9	19.7768	51.616
Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)			
n-nonane	19.9611		n-nonane	18.9659		n-nonane	18.0656		
n-butane	29.6566		n-butane	28.178		n-butane	26.8403		
helium	7.41414		helium	7.04449		helium	6.71008		
Physical State			Physical State			Physical State			
liquid,vapour			liquid,vapour			liquid,vapour			

xbutano=0.96

xbutano=0.98

xbutano=0.999

inlet stream	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	20.6192	49.2777	4.9	21.4704	47.1426	4.9	22.2871	45.2795
Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits(kg/h)			
n-nonane	17.2472		n-nonane	16.4999		n-nonane	15.8478		
n-butane	25.6244		n-butane	24.5142		n-butane	23.5453		
helium	6.4061		helium	6.12854		helium	5.88633		
Physical State			Physical State			Physical State			
liquid,vapour			liquid,vapour			liquid,vapour			

stream S1	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	50.0946	24.5994	4.9	50.0946	24.0239	4.9	50.0946	23.5218
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
	n-butane	24.5994		n-butane	24.0239		n-butane	23.5218	
	helium	0		helium	0		helium	0	
	Physical State			Physical State			Physical State		
	vapour			vapour			vapour		

stream S2	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	50.0946	24.5994	4.9	50.0946	24.0239	4.9	50.0946	23.5218
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
	n-butane	24.5994		n-butane	24.0239		n-butane	23.5218	
	helium	0		helium	0		helium	0	
	Physical State			Physical State			Physical State		
	liquid			liquid			liquid		

stream S3	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	-7.53744	31.0055	4.9	-7.1054	30.1524	4.9	-6.70297	29.4081
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
	n-butane	24.5994		n-butane	24.0239		n-butane	23.5218	
	helium	6.4061		helium	6.12854		helium	5.88633	
	Physical State			Physical State			Physical State		
	vapour			vapour			vapour		

stream S4	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	50	42.8716	4.9	50	41.0141	4.9	50	39.3931
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	17.2472		n-nonane	16.4999		n-nonane	15.8478	
	n-butane	25.6244		n-butane	24.5142		n-butane	23.5453	
	helium	0		helium	0		helium	0	
	Physical State			Physical State			Physical State		
	liquid			liquid			liquid		

stream S5	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	68.4206	42.8716	4.9	71.2305	41.0141	4.9	75.3911	39.3931
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	17.2472		n-nonane	16.4999		n-nonane	15.8478	
n-butane	25.6244		n-butane	24.5142		n-butane	23.5453		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid,vapour			liquid,vapour			liquid,vapour			

stream S6	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	167.337	18.2722	4.9	192.132	16.9902	4.9	220.822	15.8714
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	17.2472		n-nonane	16.4999		n-nonane	15.8478	
n-butane	1.02498		n-butane	0.490283		n-butane	0.023545		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid			liquid			liquid			

stream S7	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	55	18.2722	4.9	55	16.9902	4.9	55	15.8714
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	17.2472		n-nonane	16.4999		n-nonane	15.8478	
n-butane	1.02498		n-butane	0.490283		n-butane	0.023545		
helium	0		helium	0		helium	0		
Physical State			Physical State			Physical State			
liquid			liquid			liquid			

stream S8	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	50	6.4061	4.9	50	6.12854	4,9	50	5.88633
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
n-butane	0		n-butane	0		n-butane	0		
helium	6.4061		helium	6.12854		helium	5.88633		
Physical State			Physical State			Physical State			
vapour			vapour			vapour			

stream Sxx	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	-15.2213	31.0055	4.9	-15.0284	30.1524	4.9	-14.8472	29.4081
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	0		n-nonane	0		n-nonane	0	
	n-butane	24.5994		n-butane	24.0239		n-butane	23.5218	
	helium	6.4061		helium	6.12854		helium	5.88633	
	Physical State			Physical State			Physical State		
	liquid,vapour			liquid,vapour			liquid,vapour		
outlet	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)	P(atm)	T(°C)	Q(kg/h)
	4.9	20.6192	49.2777	4.9	21.4704	47.1426	4.9	22.2871	45.2795
	Partial Debits (kg/h)			Partial Debits (kg/h)			Partial Debits (kg/h)		
	n-nonane	17.2472		n-nonane	16.4999		n-nonane	15.8478	
	n-butane	25.6244		n-butane	24.5142		n-butane	23.5453	
	helium	6.4061		helium	6.12854		helium	5.88633	
	Physical State			Physical State			Physical State		
	liquid,vapour			liquid,vapour			liquid,vapour		

Appendix F – 2D and 3D graphics concerning modified mass fraction for butane, nonane and helium

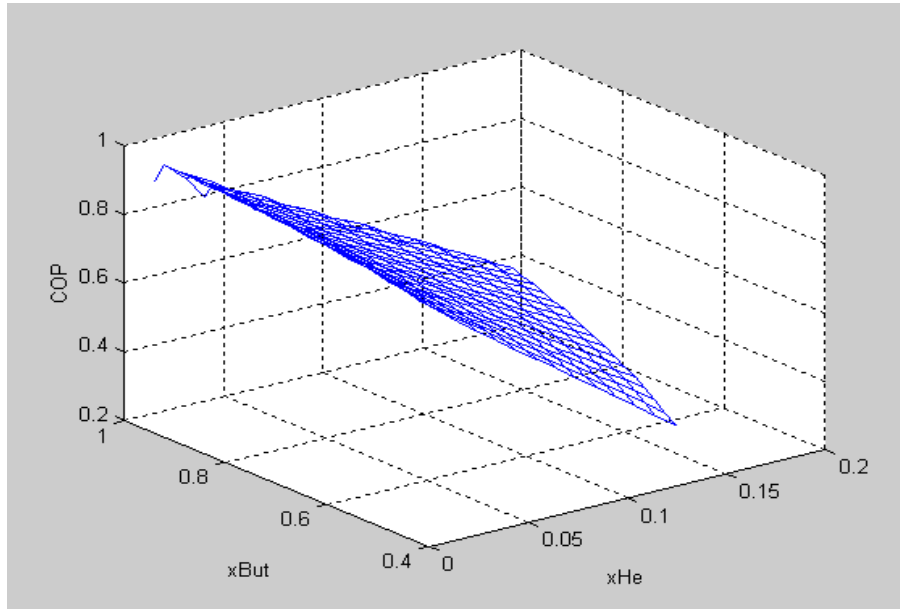


Figure F1 - Mass fraction of butane and helium versus coefficient of performance (3D chart)

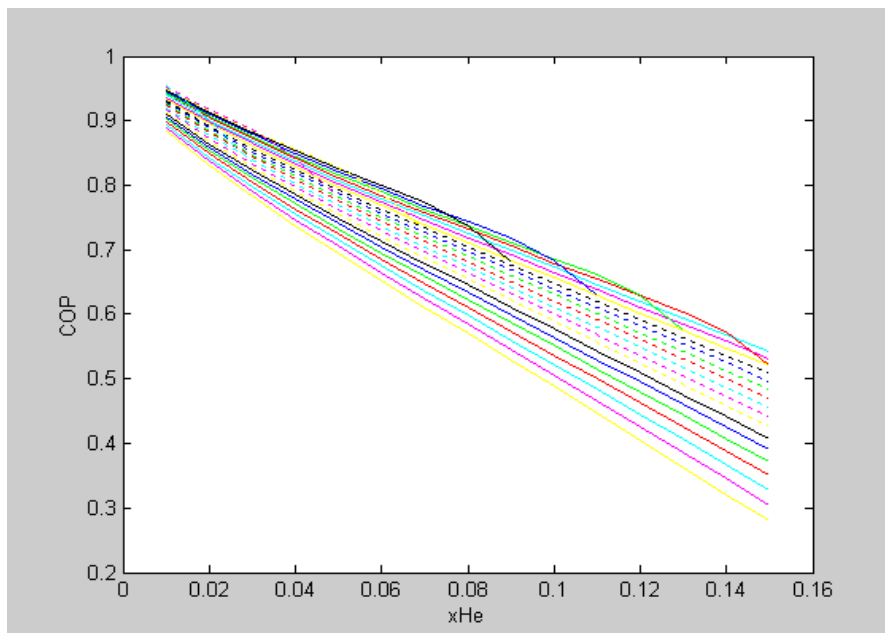


Figure F2 - Mass fraction of butane and helium versus coefficient of performance (2D chart)

Appendix G – Values for COP considering mass fraction alterations

Table G1 – Variation of COP concerning mass fractions of helium and butane

x_{butane}	COP														
	$x_{\text{He}}=0,01$	$x_{\text{He}}=0,02$	$x_{\text{He}}=0,03$	$x_{\text{He}}=0,04$	$x_{\text{He}}=0,05$	$x_{\text{He}}=0,06$	$x_{\text{He}}=0,07$	$x_{\text{He}}=0,08$	$x_{\text{He}}=0,09$	$x_{\text{He}}=0,1$	$x_{\text{He}}=0,11$	$x_{\text{He}}=0,12$	$x_{\text{He}}=0,13$	$x_{\text{He}}=0,14$	$x_{\text{He}}=0,15$
0,50	0,8840	0,8303	0,7827	0,7380	0,6950	0,6530	0,6115	0,5703	0,5291	0,4879	0,4467	0,4053	0,3637	0,3212	0,2799
0,52	0,8889	0,8367	0,7904	0,7470	0,7054	0,6647	0,6246	0,5848	0,5451	0,5054	0,4656	0,4258	0,3857	0,3455	0,3052
0,54	0,8936	0,8428	0,7976	0,7555	0,7151	0,6757	0,6368	0,5983	0,5599	0,5216	0,4833	0,4448	0,4063	0,3676	0,3286
0,56	0,8980	0,8485	0,8045	0,7635	0,7242	0,6859	0,6483	0,6110	0,5738	0,5368	0,4997	0,4626	0,4254	0,3880	0,3505
0,58	0,9021	0,8538	0,8109	0,7710	0,7328	0,6956	0,6590	0,6229	0,5869	0,5510	0,5152	0,4793	0,4433	0,4072	0,3709
0,60	0,9061	0,8589	0,8171	0,7781	0,7409	0,7047	0,6692	0,6341	0,5991	0,5644	0,5297	0,4949	0,4601	0,4251	0,3901
0,62	0,9098	0,8637	0,8228	0,7848	0,7485	0,7133	0,6788	0,6446	0,6107	0,5770	0,5433	0,5096	0,4758	0,4420	0,4081
0,64	0,9134	0,8683	0,8284	0,7912	0,7558	0,7215	0,6878	0,6546	0,6217	0,5889	0,5562	0,5235	0,4907	0,4579	0,4250
0,66	0,9167	0,8727	0,8336	0,7973	0,7627	0,7292	0,6964	0,6641	0,6320	0,6001	0,5683	0,5365	0,5047	0,4729	0,4410
0,68	0,9200	0,8769	0,8386	0,8030	0,7693	0,7366	0,7046	0,6730	0,6418	0,6108	0,5798	0,5489	0,5180	0,4871	0,4561
0,70	0,9231	0,8809	0,8434	0,8086	0,7755	0,7436	0,7123	0,6816	0,6511	0,6209	0,5907	0,5607	0,5306	0,5005	0,4703
0,72	0,9260	0,8847	0,8479	0,8139	0,7815	0,7503	0,7197	0,6897	0,6600	0,6305	0,6011	0,5718	0,5425	0,5132	0,4839
0,74	0,9289	0,8884	0,8523	0,8189	0,7872	0,7566	0,7268	0,6974	0,6684	0,6396	0,6110	0,5824	0,5539	0,5253	0,4967
0,76	0,9316	0,8919	0,8565	0,8238	0,7927	0,7627	0,7335	0,7048	0,6765	0,6483	0,6204	0,5925	0,5647	0,5368	0,5090
0,78	0,9342	0,8953	0,8606	0,8284	0,7980	0,7686	0,7400	0,7119	0,6842	0,6567	0,6293	0,6021	0,5749	0,5478	0,5206
0,80	0,9368	0,8985	0,8644	0,8329	0,8030	0,7742	0,7460	0,7187	0,6915	0,6646	0,6379	0,6113	0,5847	0,5582	0,5317
0,82	0,9392	0,9016	0,8682	0,8372	0,8078	0,7796	0,7521	0,7251	0,6986	0,6737	0,6461	0,6200	0,5941	0,5681	0,5422
0,84	0,9416	0,9047	0,8717	0,8413	0,8125	0,7847	0,7578	0,7313	0,7053	0,6795	0,6539	0,6284	0,6030	0,5775	0,5511
0,86	0,9438	0,9076	0,8752	0,8453	0,8169	0,7897	0,7632	0,7373	0,7117	0,6864	0,6613	0,6293	0,5763		
0,88	0,9460	0,9104	0,8785	0,8491	0,8212	0,7944	0,7684	0,7429	0,7178	0,6888	0,6293				
0,90	0,9481	0,9130	0,8817	0,8527	0,8253	0,7990	0,7734	0,7368	0,6807						
0,92	0,9501	0,9156	0,8848	0,8562	0,8292	0,7893	0,7311								
0,94	0,9520	0,9180	0,8876	0,8429	0,7819										
0,96	0,9538	0,9009	0,8351												
0,98	0,8954														

Appendix H – Values for COP and outlet temperature of the evaporator concerning all the alterations made relatively to the mass fraction

To be noticed that the bold values correspond to the maximum achieve for different composition of helium; the blue values correspond to the correct values concerning the feasibility of the cycle more concretely related to the outlet temperature of the evaporator and temperature from the bottom of the bubble pump (unfortunately these values are related with the lower values for COP); the last values, at green, are related with the estimative that must be made to obtain a value for COP, for these estimative the obtain values for the evaporator and bubble pump should not be considered.

Table H1 - Variation of COP considering mass fraction of helium at 0.01

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.01	0.5	0.49	0.884	35.809	142.103
0.01	0.52	0.47	0.8889	36.2396	138.19
0.01	0.54	0.45	0.8936	36.6447	134.282
0.01	0.56	0.43	0.898	37.0264	130.386
0.01	0.58	0.41	0.9021	37.3867	126.505
0.01	0.6	0.39	0.9061	37.7274	122.644
0.01	0.62	0.37	0.9098	38.05	118.806
0.01	0.64	0.35	0.9134	38.3561	114.993
0.01	0.66	0.33	0.9167	38.6468	111.206
0.01	0.68	0.31	0.92	38.9233	107.445
0.01	0.7	0.29	0.9231	39.1866	103.711
0.01	0.72	0.27	0.926	39.4376	100.001
0.01	0.74	0.25	0.9289	39.6772	96.314
0.01	0.76	0.23	0.9316	39.9062	92.6472
0.01	0.78	0.21	0.9342	40.1253	88.9973
0.01	0.8	0.19	0.9368	40.335	85.3603
0.01	0.82	0.17	0.9392	40.5361	81.7316
0.01	0.84	0.15	0.9416	40.7289	78.1058
0.01	0.86	0.13	0.9438	40.9141	74.4767
0.01	0.88	0.11	0.946	41.092	70.837
0.01	0.9	0.09	0.9481	41.2631	67.1784
0.01	0.92	0.07	0.9501	41.4278	63.4903
0.01	0.94	0.05	0.952	41.5864	59.7597
0.01	0.96	0.03	0.9538	41.7393	55.9679
0.01	0.98	0.01	0.8954	41.8867	52.0856

Table H2 - Variation of COP considering the mass fraction of helium of 0.02

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.02	0.5	0.48	0.8303	26.5389	141.104
0.02	0.52	0.46	0.8367	27.1459	137.152
0.02	0.54	0.44	0.8428	27.721	133.208
0.02	0.56	0.42	0.8485	28.2667	129.275
0.02	0.58	0.4	0.8538	28.7853	125.36
0.02	0.6	0.38	0.8589	29.279	121.467
0.02	0.62	0.36	0.8637	29.7494	117.597
0.02	0.64	0.34	0.8683	30.1983	113.753
0.02	0.66	0.32	0.8727	30.6271	109.937
0.02	0.68	0.3	0.8769	31.0372	106.147
0.02	0.7	0.28	0.8809	31.4299	102.383
0.02	0.72	0.26	0.8847	31.8062	98.644
0.02	0.74	0.24	0.8884	32.1672	94.9273
0.02	0.76	0.22	0.8919	32.5138	91.2301
0.02	0.78	0.2	0.8953	32.847	87.5486
0.02	0.8	0.18	0.8985	33.1674	83.8785
0.02	0.82	0.16	0.9016	33.4758	80.2147
0.02	0.84	0.14	0.9047	33.7729	76.5513
0.02	0.86	0.12	0.9076	34.0593	72.8815
0.02	0.88	0.1	0.9104	34.3357	69.1973
0.02	0.9	0.08	0.913	34.6024	65.4892
0.02	0.92	0.06	0.9156	34.8601	61.7455
0.02	0.94	0.04	0.918	35.1092	57.9503
0.02	0.96	0.02	0.9009	35.3501	54.0803

Table H3 - Variation of COP considering the mass fraction of helium of 0.03

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.03	0.5	0.47	0.7827	19.7404	140.085
0.03	0.52	0.45	0.7904	20.437	136.094
0.03	0.54	0.43	0.7976	21.1	132.111
0.03	0.56	0.41	0.8045	21.7318	128.143
0.03	0.58	0.39	0.8109	22.3348	124.194
0.03	0.6	0.37	0.8171	22.9109	120.267
0.03	0.62	0.35	0.8228	23.4621	116.366
0.03	0.64	0.33	0.8284	23.9899	112.491
0.03	0.66	0.31	0.8336	24.4961	108.644
0.03	0.68	0.29	0.8386	24.9818	104.825
0.03	0.7	0.27	0.8434	25.4485	101.031
0.03	0.72	0.25	0.8479	25.8972	97.2622
0.03	0.74	0.23	0.8523	26.329	93.515
0.03	0.76	0.21	0.8565	26.745	89.7862
0.03	0.78	0.19	0.8606	27.1459	86.0719
0.03	0.8	0.17	0.8644	27.5326	82.3672
0.03	0.82	0.15	0.8682	27.906	78.6665
0.03	0.84	0.13	0.8717	28.2667	74.9635
0.03	0.86	0.11	0.8752	28.6153	71.2506
0.03	0.88	0.09	0.8785	28.9526	67.5189
0.03	0.9	0.07	0.8817	29.279	63.7577
0.03	0.92	0.05	0.8848	29.595	59.9533
0.03	0.94	0.03	0.8876	29.9013	56.0864
0.03	0.96	0.01	0.8351	30.1983	52.1262

Table H4 - Variation of COP considering the mass fraction of helium of 0.04

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.04	0.5	0.46	0.738	14.4114	139.046
0.04	0.52	0.44	0.747	15.1588	135.014
0.04	0.54	0.42	0.7555	15.8722	130.994
0.04	0.56	0.4	0.7635	16.5541	126.989
0.04	0.58	0.38	0.771	17.2066	123.005
0.04	0.6	0.36	0.7781	17.8317	119.045
0.04	0.62	0.34	0.7848	18.4314	115.112
0.04	0.64	0.32	0.7912	19.0072	111.206
0.04	0.66	0.3	0.7973	19.5606	107.328
0.04	0.68	0.28	0.803	20.0931	103.478
0.04	0.7	0.26	0.8086	20.6058	99.6543
0.04	0.72	0.24	0.8139	21.1	95.8546
0.04	0.74	0.22	0.8189	21.5767	92.0759
0.04	0.76	0.2	0.8238	22.0368	88.3145
0.04	0.78	0.18	0.8284	22.4812	84.566
0.04	0.8	0.16	0.8329	22.9109	80.8251
0.04	0.82	0.14	0.8372	23.3265	77.0857
0.04	0.84	0.12	0.8413	23.7288	73.3408
0.04	0.86	0.1	0.8453	24.1185	69.582
0.04	0.88	0.08	0.8491	24.4961	65.7994
0.04	0.9	0.06	0.8527	24.8622	61.9808
0.04	0.92	0.04	0.8562	25.2175	58.1097
0.04	0.94	0.02	0.8429	25.5623	54.1619

Table H5 - Variation of COP considering the mass fraction of helium of 0.05

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.05	0.5	0.45	0.695	10.0531	137.984
0.05	0.52	0.43	0.7054	10.831	133.913
0.05	0.54	0.41	0.7151	11.5751	129.854
0.05	0.56	0.39	0.7242	12.2878	125.813
0.05	0.58	0.37	0.7328	12.9711	121.794
0.05	0.6	0.35	0.7409	13.6271	117.8
0.05	0.62	0.33	0.7485	14.2576	113.834
0.05	0.64	0.31	0.7558	14.8641	109.897
0.05	0.66	0.29	0.7627	15.4481	105.988
0.05	0.68	0.27	0.7693	16.0111	102.107
0.05	0.7	0.25	0.7755	16.5541	98.2518
0.05	0.72	0.23	0.7815	17.0783	94.4203
0.05	0.74	0.21	0.7872	17.5848	90.6091
0.05	0.76	0.19	0.7927	18.0746	86.8138
0.05	0.78	0.17	0.798	18.5484	83.0297
0.05	0.8	0.15	0.803	19.0072	79.2508
0.05	0.82	0.13	0.8078	19.4517	75.4706
0.05	0.84	0.11	0.8125	19.8826	71.6813
0.05	0.86	0.09	0.8169	20.3005	67.8735
0.05	0.88	0.07	0.8212	20.7061	64.0361
0.05	0.9	0.05	0.8253	21.1	60.1549
0.05	0.92	0.03	0.8292	21.4827	56.2097
0.05	0.94	0.01	0.7819	21.8546	52.1685

Table H6 - Variation of COP considering the mass fraction of helium of 0.06

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.06	0.5	0.44	0.653	6.38147	136.9
0.06	0.52	0.42	0.6647	7.17827	132.788
0.06	0.54	0.4	0.6757	7.9416	128.691
0.06	0.56	0.38	0.6859	8.67381	124.613
0.06	0.58	0.36	0.6956	9.37701	120.559
0.06	0.6	0.34	0.7047	10.0531	116.531
0.06	0.62	0.32	0.7133	10.7038	112.532
0.06	0.64	0.3	0.7215	11.3307	108.563
0.06	0.66	0.28	0.7292	11.9352	104.622
0.06	0.68	0.26	0.7366	12.5187	100.709
0.06	0.7	0.24	0.7436	13.0823	96.8226
0.06	0.72	0.22	0.7503	13.6271	92.9585
0.06	0.74	0.2	0.7566	14.1542	89.1135
0.06	0.76	0.18	0.7627	14.6645	85.283
0.06	0.78	0.16	0.7686	15.1588	81.4616
0.06	0.8	0.14	0.7742	15.6381	77.6428
0.06	0.82	0.12	0.7796	16.1029	73.8195
0.06	0.84	0.1	0.7847	16.5541	69.9828
0.06	0.86	0.08	0.7897	16.9922	66.1225
0.06	0.88	0.06	0.7944	17.4179	62.2259
0.06	0.9	0.04	0.799	17.8317	58.2758
0.06	0.92	0.02	0.7893	18.2342	54.2469

Table H7 - Variation of COP considering the mass fraction of helium of 0.07

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.07	0.5	0.43	0.6115	3.21976	135.794
0.07	0.52	0.41	0.6246	4.02826	131.641
0.07	0.54	0.39	0.6368	4.80378	127.505
0.07	0.56	0.37	0.6483	5.5486	123.39
0.07	0.58	0.35	0.659	6.26476	119.3
0.07	0.6	0.33	0.6692	6.95413	115.238
0.07	0.62	0.31	0.6788	7.6184	111.206
0.07	0.64	0.29	0.6878	8.25909	107.204
0.07	0.66	0.27	0.6964	8.8776	103.231
0.07	0.68	0.25	0.7046	9.47521	99.2856
0.07	0.7	0.23	0.7123	10.0531	95.3659
0.07	0.72	0.21	0.7197	10.6123	91.4681
0.07	0.74	0.19	0.7268	11.1539	87.5881
0.07	0.76	0.17	0.7335	11.6788	83.7208
0.07	0.78	0.15	0.74	12.1878	79.8602
0.07	0.8	0.13	0.746	12.6817	75.9994
0.07	0.82	0.11	0.7521	13.1612	72.1302
0.07	0.84	0.09	0.7578	13.6271	68.2431
0.07	0.86	0.07	0.7632	14.08	64.3263
0.07	0.88	0.05	0.7684	14.5204	60.365
0.07	0.9	0.03	0.7734	14.9489	56.3382
0.07	0.92	0.01	0.7311	15.366	52.2127

Table H8 - Variation of COP considering the mass fraction of helium of 0.08

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.08	0.5	0.42	0.5703	0.450716	134.664
0.08	0.52	0.4	0.5848	1.26634	130.47
0.08	0.54	0.38	0.5983	2.04948	126.295
0.08	0.56	0.36	0.611	2.80235	122.142
0.08	0.58	0.34	0.6229	3.52697	118.017
0.08	0.6	0.32	0.6341	4.22514	113.92
0.08	0.62	0.3	0.6446	4.89852	109.854
0.08	0.64	0.28	0.6546	5.5486	105.818
0.08	0.66	0.26	0.6641	6.17674	101.813
0.08	0.68	0.24	0.673	6.78421	97.8342
0.08	0.7	0.22	0.6816	7.37214	93.8807
0.08	0.72	0.2	0.6897	7.9416	89.948
0.08	0.74	0.18	0.6974	8.49355	86.0316
0.08	0.76	0.16	0.7048	9.02891	82.1258
0.08	0.78	0.14	0.7119	9.5485	78.2241
0.08	0.8	0.12	0.7187	10.0531	74.3187
0.08	0.82	0.1	0.7251	10.5434	70.4008
0.08	0.84	0.08	0.7313	11.0201	66.4595
0.08	0.86	0.06	0.7373	11.4839	62.4814
0.08	0.88	0.04	0.7429	11.9352	58.4489
0.08	0.9	0.02	0.7368	12.3747	54.3356

Table H9 - Variation of COP considering the mass fraction of helium of 0.09

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.09	0.5	0.41	0.5291	-2.00726	133.511
0.09	0.52	0.39	0.5451	-1.18757	129.275
0.09	0.54	0.37	0.5599	-0.399883	125.06
0.09	0.56	0.35	0.5738	0.35798	120.87
0.09	0.58	0.33	0.5869	1.08798	116.708
0.09	0.6	0.31	0.5991	1.7919	112.576
0.09	0.62	0.29	0.6107	2.47134	108.476
0.09	0.64	0.27	0.6217	3.12778	104.406
0.09	0.66	0.25	0.632	3.76255	100.367
0.09	0.68	0.23	0.6418	4.37687	96.3544
0.09	0.7	0.21	0.6511	4.97187	92.3659
0.09	0.72	0.19	0.66	5.5486	88.397
0.09	0.74	0.17	0.6684	6.10799	84.4426
0.09	0.76	0.15	0.6765	6.65094	80.4964
0.09	0.78	0.13	0.6842	7.17827	76.5513
0.09	0.8	0.11	0.6915	7.69072	72.5987
0.09	0.82	0.09	0.6986	8.18902	68.6286
0.09	0.84	0.07	0.7053	8.67381	64.6289
0.09	0.86	0.05	0.7117	9.14571	60.5841
0.09	0.88	0.03	0.7178	9.60529	56.4723
0.09	0.9	0.01	0.6807	10.0531	52.2587

Table H10 - Variation of COP considering the mass fraction of butane of 0.1

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.1	0.5	0.4	0.4879	-4.21316	132.332
0.1	0.52	0.38	0.5054	-3.3915	128.055
0.1	0.54	0.36	0.5216	-2.60137	123.8
0.1	0.56	0.34	0.5368	-1.84065	119.572
0.1	0.58	0.32	0.551	-1.1074	115.373
0.1	0.6	0.3	0.5644	-0.399883	111.206
0.1	0.62	0.28	0.577	-0.283479	107.071
0.1	0.64	0.26	0.5889	-0.944124	102.967
0.1	0.66	0.24	0.6001	1.58337	98.8925
0.1	0.68	0.22	0.6108	2.20241	94.845
0.1	0.7	0.2	0.6209	2.80235	90.8203
0.1	0.72	0.18	0.6305	3.38422	86.8138
0.1	0.74	0.16	0.6396	3.94894	82.8197
0.1	0.76	0.14	0.6483	4.49738	78.831
0.1	0.78	0.12	0.6567	5.03035	74.8399
0.1	0.8	0.1	0.6646	5.5486	70.837
0.1	0.82	0,08	0,6737	6,05281	66,8111
0.1	0.84	0.06	0.6795	6.54363	62.7481
0.1	0.86	0.04	0.6864	7.02166	58.6296
0.1	0.88	0.02	0.6838	7.48748	54.4281

Table H11 - Variation of COP considering the mass fraction of helium of 0.11

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.11	0.5	0.39	0.4467	-6.21095	131.129
0.11	0.52	0.37	0.4656	-5.38878	126.81
0.11	0.54	0.35	0.4833	-4.5977	122.514
0.11	0.56	0.33	0.4997	-3.83562	118.248
0.11	0.58	0.31	0.5152	-3.10065	114.012
0.11	0.6	0.29	0.5297	-2.39107	109.808
0.11	0.62	0.27	0.5433	-1.70534	105.638
0.11	0.64	0.25	0.5562	-1.04204	101.499
0.11	0.66	0.23	0.5683	-0.399883	97.3888
0.11	0.68	0.21	0.5798	0.222314	93.305
0.11	0.7	0.19	0.5907	0.825635	89.2429
0.11	0.72	0.17	0.6011	1.41108	85.1971
0.11	0.74	0.15	0.611	1.97957	81.1612
0.11	0.76	0.13	0.6204	2.53195	77.1278
0.11	0.78	0.11	0.6293	3.06902	73.0879
0.11	0.8	0.09	0.6379	3.59151	69.0312
0.11	0.82	0.07	0.6461	4.10009	64.9449
0.11	0.84	0.05	0.6539	4.59541	60.8129
0.11	0.86	0.03	0.6613	5.07806	56.6123
0.11	0.88	0.01	0.6293	5.5486	52.3069

Table H12 - Variation of COP considering the mass fraction of helium of 0.12

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.12	0.5	0.38	0.4053	-8.3423	129.9
0.12	0.52	0.36	0.4258	-7.21259	125.538
0.12	0.54	0.34	0.4448	-6.42162	121.202
0.12	0.56	0.32	0.4626	-5.65927	116.896
0.12	0.58	0.3	0.4793	-4.92368	112.623
0.12	0.6	0.28	0.4949	-4.21316	108.383
0.12	0.62	0.26	0.5096	-3.52619	104.176
0.12	0.64	0.24	0.5235	-2.86138	100.001
0.12	0.66	0.22	0.5365	-2.21746	95.8546
0.12	0.68	0.2	0.5489	-1.59327	91.7333
0.12	0.7	0.18	0.5607	-0.987737	87.6321
0.12	0.72	0.16	0.5718	-0.399883	83.5452
0.12	0.74	0.14	0.5824	0.1712	79.4655
0.12	0.76	0.12	0.5925	0.726349	75.3846
0.12	0.78	0.1	0.6021	1.26634	71.2928
0.12	0.8	0.08	0.6113	1.7919	67.1784
0.12	0.82	0.06	0.62	2.3037	63.0266
0.12	0.84	0.04	0.6284	2.80235	58.8184
0.12	0.86	0.02	0.6293	3.28845	54.5248

Table H13 - Variation of COP considering the mass fraction of helium of 0.13

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.13	0.5	0.37	0.3637	80.941	66.1556
0.13	0.52	0.35	0.3857	-8.88886	124.239
0.13	0.54	0.33	0.4063	-8.09877	119.863
0.13	0.56	0.31	0.4254	-7.33694	115.517
0.13	0.58	0.29	0.4433	-6.60154	111.206
0.13	0.6	0.27	0.4601	-5.89091	106.929
0.13	0.62	0.25	0.4758	-5.20354	102.685
0.13	0.64	0.23	0.4907	-4.53808	98.4727
0.13	0.66	0.21	0.5047	-3.89326	94.2886
0.13	0.68	0.19	0.518	-3.26794	90.1284
0.13	0.7	0.17	0.5306	-2.66108	85.9866
0.13	0.72	0.15	0.5425	-2.07171	81.8567
0.13	0.74	0.13	0.5539	-1.49892	77.7306
0.13	0.76	0.11	0.5647	-0.941901	73.5994
0.13	0.78	0.09	0.5749	-0.399883	69.452
0.13	0.8	0.07	0.5847	0.127846	65.2752
0.13	0.82	0.05	0.5941	0.641947	61.0519
0.13	0.84	0.03	0.603	1.14304	56.7587
0.13	0.86	0.01	0.5763	1.63169	52.3572

Table H14 - Variation of COP considering the mass fraction of helium of 0.14

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.14	0.5	0.36	0.3212	15.34	111.961
0.14	0.52	0.34	0.3455	76.6209	64.6809
0.14	0.54	0.32	0.3676	73.8073	64.3398
0.14	0.56	0.3	0.388	-8.88886	114.11
0.14	0.58	0.28	0.4072	-8.15425	109.76
0.14	0.6	0.26	0.4251	-7.44412	105.445
0.14	0.62	0.24	0.442	-6.75699	101.163
0.14	0.64	0.22	0.4579	-6.09151	96.9127
0.14	0.66	0.2	0.4729	-5.44645	92.6897
0.14	0.68	0.18	0.4871	-4.82068	88.4891
0.14	0.7	0.16	0.5005	-4.21316	84.3048
0.14	0.72	0.14	0.5132	-3.62294	80.1295
0.14	0.74	0.12	0.5253	-3.04914	75.9545
0.14	0.76	0.1	0.5368	-2.49095	71.7695
0.14	0.78	0.08	0.5478	-1.9476	67.5624
0.14	0.8	0.06	0.5582	-1.4184	63.3179
0.14	0.82	0.04	0.5681	-0.902697	59.0157
0.14	0.84	0.02	0.5725	-0.399883	54.626

Table H15 - Variation of COP considering the mass fraction of helium of 0.15

x_{He}	x_{But}	x_{Non}	COP	$T_{EVout}(^{\circ}C)$	$T_{BP\ bottom}(^{\circ}C)$
0.15	0.5	0.35	0.2799	-12.6938	126.05
0.15	0.52	0.33	0.3052	73.793	64.499
0.15	0.54	0.31	0.3286	70.9583	64.1281
0.15	0.56	0.29	0.3505	68.0124	63.7421
0.15	0.58	0.27	0.3709	64.9441	63.3365
0.15	0.6	0.25	0.3901	-8.88886	103.93
0.15	0.62	0.23	0.4081	-8.20244	99.6095
0.15	0.64	0.21	0.425	-7.53744	95.3199
0.15	0.66	0.19	0.441	-6.89264	91.0565
0.15	0.68	0.17	0.4561	-6.26692	86.8138
0.15	0.7	0.15	0.4703	-5.65927	82.585
0.15	0.72	0.13	0.4839	-5.06874	78.3618
0.15	0.74	0.11	0.4967	-4.49446	74.1347
0.15	0.76	0.09	0.509	-3.93563	69.8923
0.15	0.78	0.07	0.5206	-3.3915	65.6206
0.15	0.8	0.05	0.5317	-2.86138	61.302
0.15	0.82	0.03	0.5422	-2.34463	56.9117
0.15	0.84	0.01	0.5211	-1.84065	52.4098