UNIVERSITY POLITEHNICA OF BUCHAREST
Faculty of Mechanical Engineering and Mechatronics
Thermotechnics Department, Engines, Thermal and Refrigeration Equipment
No. Senate Decision 847 from 09.06.2022

PHD THESIS

Studies on the possibility of increasing the energy efficiency of Cryogenic Air Separation Installations by improving the processes around distillation columns

SUMMARY

Author: ing. Marius PINTILIE

Scientific coordinator: Prof.dr.ing. Alexandru SERBAN

Author's note:

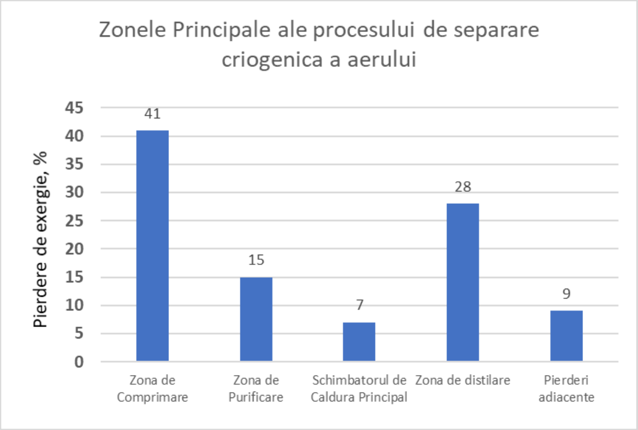
I am very honored that I had the opportunity, under the exceptional guidance of the team of professors from the Polytechnic University of Bucharest, to be able to deepen a series of theoretical processes that represent the basis of the Industry in which I have been working for over 30 years. The experience gained step by step, as well as its consolidation in the direct operational field, and I refer here to the operation of numerous air separation installations, of different sizes in the area between the North American Continent and the countries of the Middle East, would not have been possible without having constantly sought a logical explanation and without linking the observations made to the laws governing the processes in question.

I am also pleased that the idea of an experimental study has been accepted and part of its conclusions I am convinced that they will serve for a better understanding of the degree of sensitivity regarding the functioning of the unit consisting of the Low Pressure Column, the Crude Argon Column as well as the Condenser of the Crude Argon Column.

Of course, today's technique development has made available to the operator of the air separation installation a series of systems and programs designed to control and manage the efficient operation of the installation within the limits of the designed parameters and to adapt its task in line with the production needs, but the capacity of the human resource to understand at the level of detail still remains essential, also the way in which the processes in the installation are carried out and of course the need to anticipate and to compare the different operating scenarios.

There are important interactions between cold production systems and those responsible for separation processes, interactions that must be considered from the very first stages of design, first of all to ensure the maximization of advantages through their optimal integration (compression equipment, heat exchangers, expansion turbines, separation columns, cryogenic pumps and so on...).

Research and studies in the field have the objective of minimizing the irreversibility mainly in the processes used for liquefaction and separation, the most relevant processes involved in thermal integration.



Distribution of exergetic losses on the main areas of the cryogenic air separation process

Current studies and results clearly indicate that the loss of exergy in the distillation area is about 28% of the total exergy losses, that being the second largest area in terms of total exergy losses after compression.

Hence the intention was to orient the study on the direction of the distillation area, and due to the increased sensitivity in the middle zone of the Upper Column (the area of concentration in Argon), the comparative study highlighted two different solutions of designing with direct implications in the overall separation efficiency and as well with implications in the way of how the Columns are configured and constructed.

The thesis is structured in 5 basic chapters:

1. In Chapter I are presented cryogenic cycles frequently used in air separation processes. We will refer to the Linde cycle with the Simple Separation Column, to the Linde cycle with the Double Separation Column, to the Heylandt cycle, and to the Linde – Frankl cycle. For each of the listed cycles are presented their diagrams,

their representation in the Temperature- Entropy diagram, the thermal calculation as well as the main performance parameters.

Obtaining argon involves a wide study, namely the need to attach to the double column an additional simple column in order to extract the raw argon (and here we refer to the argon obtained with purity in oxygen according to the design data) and a second column in which the final separation of the argon from the traces of nitrogen takes place.

2. The second Chapter presents the distillation columns used in the cryogenic technique, the principle of fractional distillation is then presented, as well as the elements of heat and mass exchange in the distillation processes – classical plates versus filling packages.

Also here are presented the configurations of a simple column – with the aim of getting out a single component of the binary mixture oxygen - nitrogen, as well as of a double column – where are simultaneously obtained the two main components mentioned above.

The double column concept is also referring to the thermal coupling of the columns - namely the Condenser-Evaporator (also called the Main Condenser), the performance of this equipment being essential for the overall efficiency of the distillation Columns group. We will also encounter some comments on new concepts of designing distillation columns – as well as the essential factors that affect the functionality and stability of processes.

3. In the third Chapter: *Simulation and sensitivity analysis of a cryogenic air separation installation*, the analysis of the process of obtaining the main components from the air subjected to separation using the PRO II calculation program is presented. This calculation was made for stationary operating conditions,

As the air separation installations are usually subject to relevant production/consumption variations (e.g. the loading of the systems according to the variation of the day/night electricity tariff, or variations in the demand due to the specific Industry in a series of industrial applications - the steel production, etc..) it is important to proceed to a sensitivity analysis of the installation as a whole (load – unloaddynamics, low-regime operation, etc.)

4. The fourth Chapter, *The mathematical model, in stationary conditions, of the distillation area of a cryogenic air separation installation*, presents a mathematical model in stationary regime for both the distillation columns with plates and for those with filling packages. The results highlight the advantages of using packaged columns.

5. In the fifth Chapter : *Possibilities to improve the energy and exergetic efficiency of the distillation area of a cryogenic air separation unit* (ASU) are presented three directions of study - one relating to the Condenser-Evaporator located in the double distillation column, and the other two refer to modified configurations of the distillation columns.

In the second part of this last chapter are presented the results of an experimental study on two high-capacity industrial air separation installations, the first one representing an installation with classic design- classic approach into considering the setup of the Upper Column , and the second one representing an installation where the processes of preliminary separation of the argon fraction is also carried out in side of Upper Column.

It is also presented and described the new model of thermal integration of the Condenser afferent to the Crude Argon Column. All the data contained in this subchapter have as a reference the measurements made directly in the locations where the two installations activate. It was preferred to include in the comparative study, the results of the calculations that accompanied this approach to make available to those interested (students, engineers) as many results as possible, in regard to the author's practice and experience, directly in the production sites.

The entire Table of Contents of the work is below presented:

Summary

CHAPTER I

Cryogenic air separation cycles

CHAPTER II

Distillation columns used in Cryogenic technology

CHAPTER III

Simulation and sensitivity analysis of a cryogenic air separation installation

CHAPTER IV

The mathematical model, in stationary conditions, of the distillation area of a cryogenic air separation installation

CHAPTER V

A. Possibilities to improve the energy efficiency of the distillation area of a cryogenic air separation unit

B. Comparative experimental study

CHAPTER I

Cryogenic air separation cycles

In this chapter it is essential to understand first, the block configuration of an air separation installation.
The five main steps can be distinguished in any ASU unit: compression, purification, cold production, heat exchange and separation (which can be subdivided into the extraction of nitrogen, oxygen and argon). The interdependence of these functions is shown in Figure 1.1.

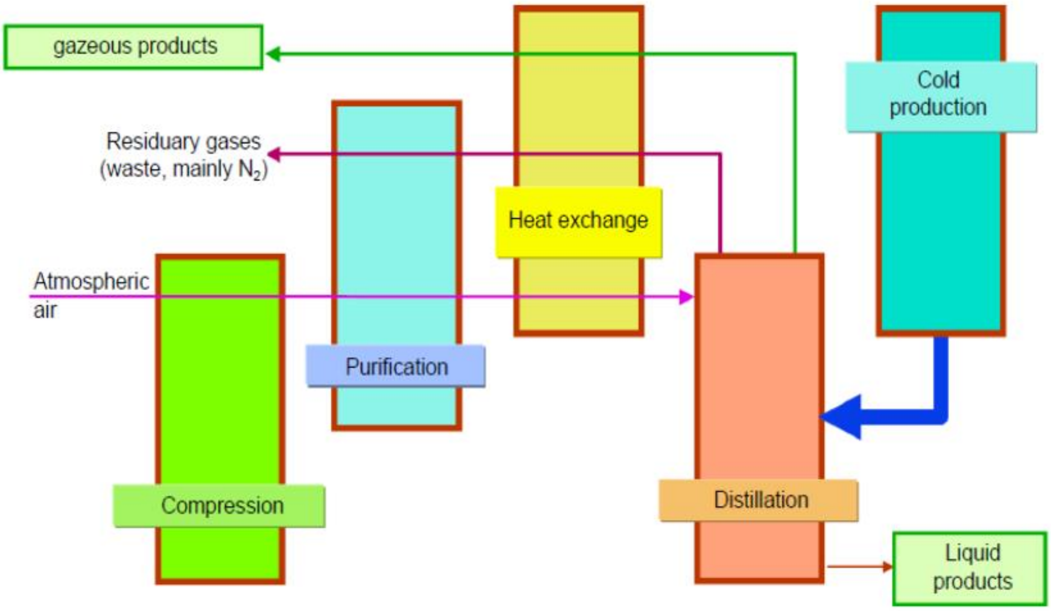


Figure 1.1. The main functions of a cryogenic air separation installation

Strictly referring to the basic cycles encountered in cryogenic technique, I can recall:

1.1.1. Linde simple column system

The simplest cryogenic air separation system is Linde's single-column system, shown in Figure 1. 2. This cycle was first used by Carl von Linde in 1902.

The presented cycle has crucial importance because in this way, the foundations were laid for obtaining the oxygen by industrial means.

When it is desired that the separated oxygen is to be in gaseous form, atmospheric air must be compressed only at a pressure of the order of 30 atm to 60 atm.

If it is necessary for oxygen to be in the form of a liquid, for an efficient operation of the separation installation, the air must be compressed at approximately 200 atm. The pressure inside the column is usually of the order of 1.3 -2 atm.

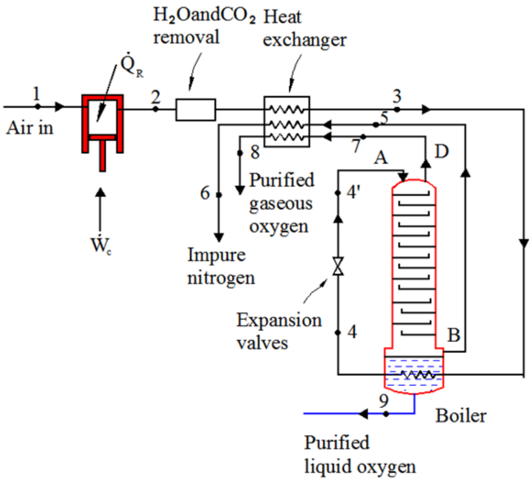


Figure 1. 2. Linde's single-column system

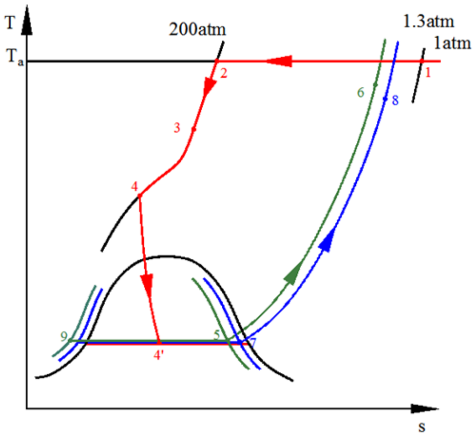
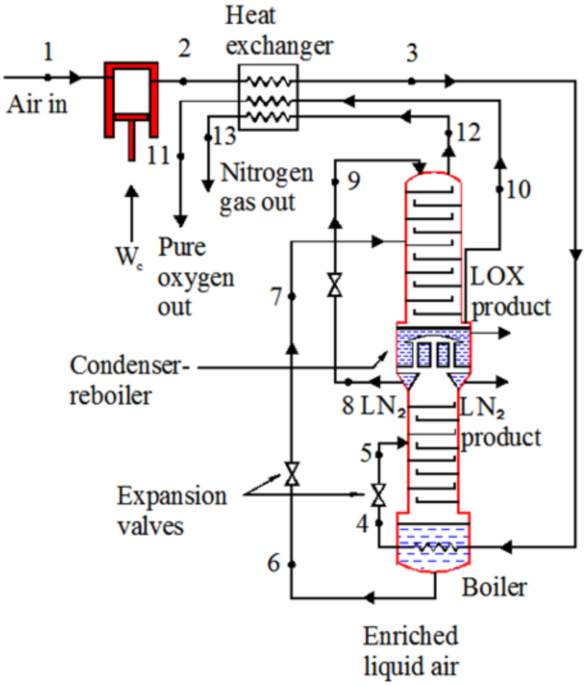


*Figura 1.3. Diagrama **T-s***

The **T-s** diagram of the Linde cycle with a simple air separation column is shown in Figure 1. 3.

1.2. Linde double-column air separation cycle

This cycle derives from the base cycle and has the characteristic use of a double column, resulting from the overlapping of two simple separation columns, thermally coupled through a condenser-evaporator. The scheme of Linde's double-column air separation system is shown in Figure 1.4, and in Figure 1.5 is the representation of the thermodynamic process in the **T-s** diagram.



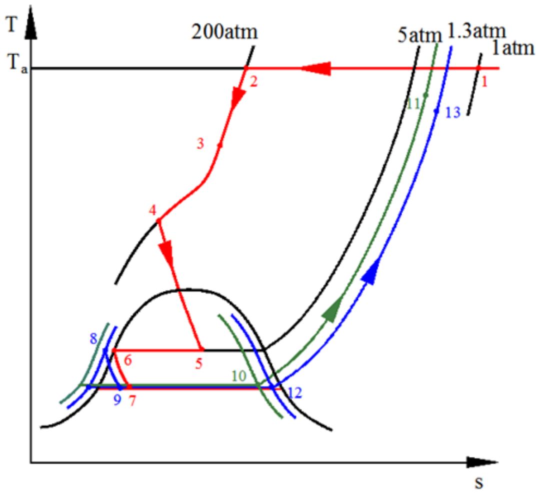
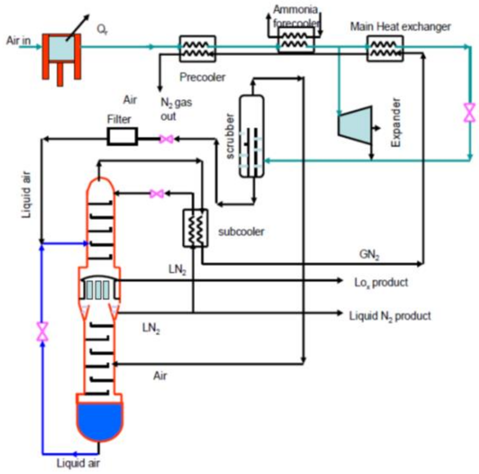


Figure 1.4. Linde double-column system

*Figure 1.5. Diagram **T-s***

The essential feature of this cycle is that the two main components in the processed air are obtained simultaneously.

1.3 Heylandt Cycle



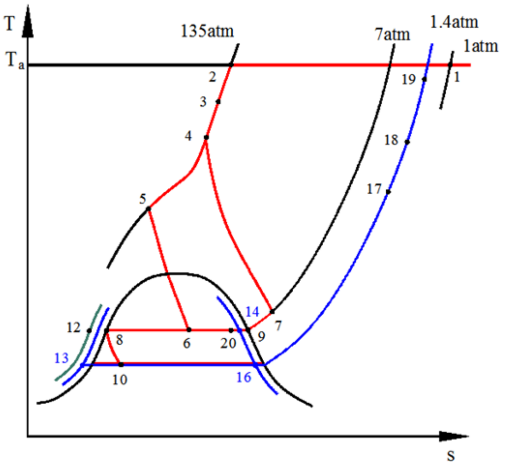


Figure 1.6. Heylandt air separation system scheme

*Figure 1.7. **T-s** diagram of the Heylandt cycle*

The key feature of the Heylandt Cycle is that for a high pressure cycle, the advantage of using of an expansion machine was used, which expands about half of the processed amount of air in tandem with a reversible heat exchanger system that participates in optimizing cold production. This cycle is widely used in the USA for plants with high production of cryogenic liquids.

1.3. Sistemul de separare Linde-Frankl

The Linde-Frankl common system was first introduced in 1950, as the cycle of operation for a plant for the production of oxygen, in which stone-filled regenerators were used. The vast majority of high-powered installations operated in this scheme even after the 70's. Currently, this technology where air purification is done using the regenerators technique is mostly abandoned and replaced by modern primary purification systems based on adsorbers with Molecular Sieves.

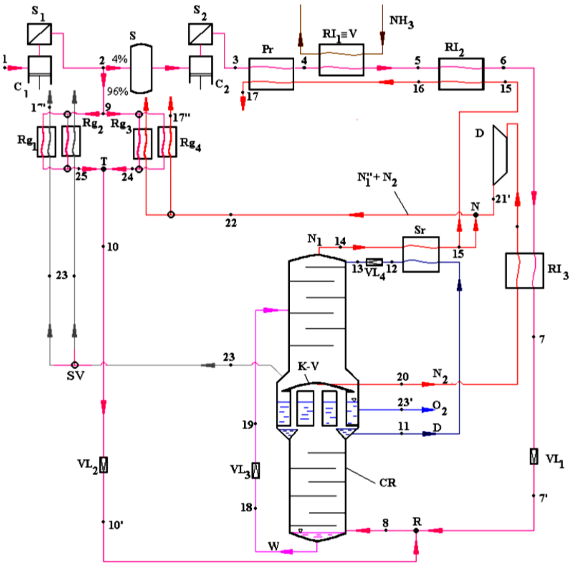


Figure 1.8. Diagram of Linde-Frankl air separation installation

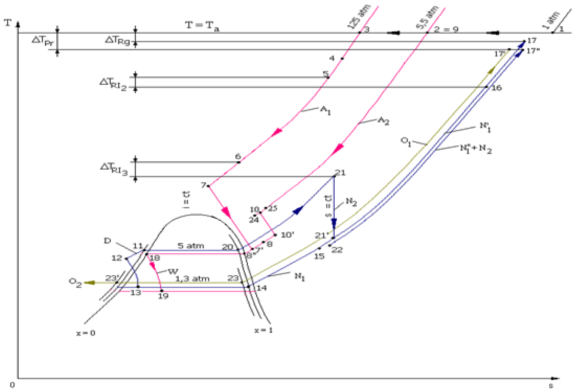


Figura 1.9. Reprezentarea ciclului Linde-Frankl în diagrama T-s

The chapter is a review of the cryogenic cycles used to separate the air components, for the situation in which air is considered as a bi-component mixture (oxygen and nitrogen).

- ✓ If only oxygen is to be obtained as a separation product, the Linde cycle with a simple separation column is used.
- ✓ If the aim is to obtain as final products the two components (oxygen and nitrogen), the other three installations presented shall be used, namely:
- ✓ the Linde-Frankl separation cycle and the Linde double-column air separation cycle, if it is desired to obtain the products in the gaseous state;
- ✓ Heylandt cycle**,** for where liquid separation products will be obtained.
- ✓ If argon is to be obtained as theaimed product, then in the plant is inserted another column (Column of CrudeArgon), or two (plus Column of Pure aAgon).

CHAPTER II

Distillation columns used in cryogenic technology

Distillation is defined as a process aimed for the separation of the components of a mixture by capitalizing on their different volatility, i.e. their preferential accumulation in the liquid or gas when the mixture is at biphasic thermodynamic equilibrium.

In a phased process as shown in Figure 2. 1. the cascade rectification process can develop only as a result of permanent imbalance, imbalance of concentration and temperature along the height of the column between the ascending flow and the descending reflux.

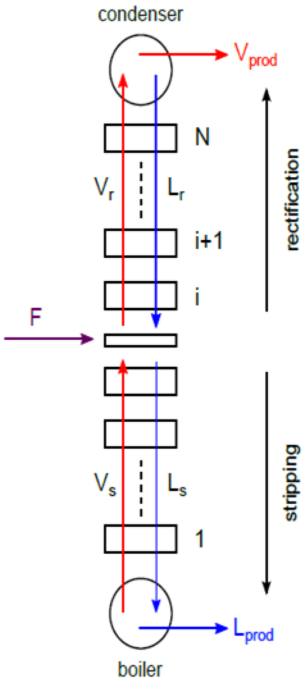


Figure 2.1. Distillation steps in separation process

A distillation step is effective if it is as close as possible to the biphasic thermodynamic equilibrium. This involves maximizing the homogeneity of the biphasic mixture and the liquid gas contact surface to improve heat and mass exchanges.

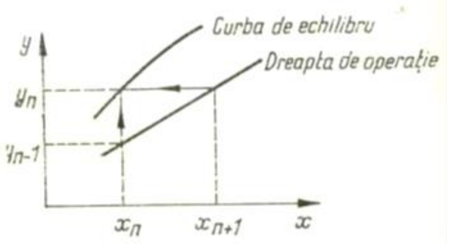


Figure 2.4. Theoretic rectification tray

The work briefly presents the calculation method and the working hypotheses for a rectification tray- in the classical versions (bubble plates) and the current ones (perforated plates) and makes a review of the constructive types of columns and the way in which the trays / filling packages are integrated.

Also, there is presented a new concept of configuration for rectification columns: columns in diabatic configuration and/ or thermally integrated columns.

The development of the technology using the filling package type plates, besides the extraordinary advantage dictated by the reduction of the pressure drop along the rectification column , it allowed the execution of columns with an impressive number of theoretical trays by reducing the height of the columns because a theoretical tray- type: filling package, requires a smaller space in height, which as an example ,allowed the almost complete separation of oxygen from the oxygen-argon mixture directly inside the dedicated Crude Argon Column,.(So, O2-Ar separation process could be based solely on rectification).

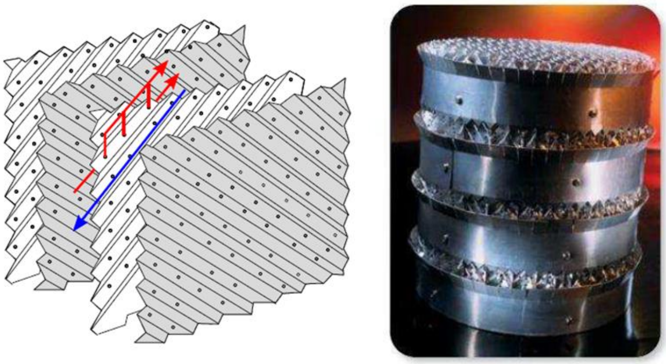


Figure 2. 10. Structured filled pack used in the technique of cryogenic air separation.

a: Juxtaposed metal sheets with examples of flow paths for liquids (blue) and gases (red)

b: cylindrical packets of juxtaposed sheets mounted in the column

In the second part of this chapter are presented the main steps in designing a correction column:

- calculation of the minimum / theoretic / real number of rectification plates/trays
- calculation of the minimum reflux ratio
- calculation of the diameter /height of a column
- calculation the pressure losses along of column height
- checking the drip condition

Due to the intensive energy consumption in cryogenic air separation systems, there is a constant concern in the study, experimentation and development of technologies that lead to an increase in the performance of distillation columns.

The main directions of research and development are and will be:

1. Improvement of the columns with filling packages, in order to diminish the negative effects regarding the biphasic flowing through the channels.
2. Thermal integration of columns, which will lead in the future to the new configurations of cryogenic air separation systems.
3. The development of high-performance mathematical models, thus overcoming a series of issues regarding the pressure losses in the column, as well as the exergetic losses around the column.

CHAPTER III

Simulation and sensitivity analysis of a cryogenic air separation installation

In this chapter is presented the analysis of the process of getting out the main components from the processed air using an adopted scheme consisting of a double column, connected with an argon column, designed to produce raw argon.

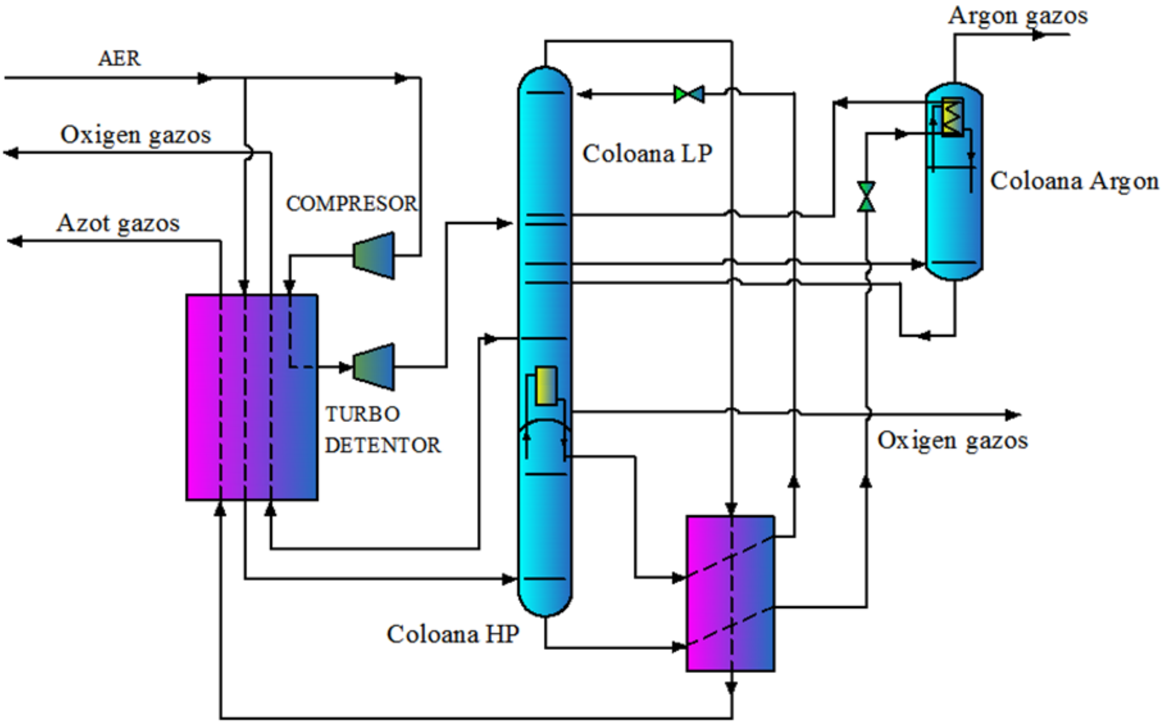


Figure 3.1. Diagram of the analyzed installation

It is essential to understand that the consideration of the working pressures in the two main columns must lead to the "inversion" of the equilibrium temperatures for the nitrogen and oxygen components in the sense that the gas nitrogen obtained at the top of the Lower Column represents the source of heat for the vaporization of oxygen in the Condenser-Evaporator that thermally engages the Lower and the Upper columns.

To understand what is needed to maintain the pressure in the Lower Column to the desired value, it is necessary to analyze the functionality of the Condenser-Evaporator. The thermal load of its condensation capability is determined by:

- condensing surface; the greater it is, the greater the heat transfer takes place and vice versa;
- the difference in temperature ΔT between the liquid oxygen part and the liquid nitrogen part; the greater the difference, the more heat is transferred and vice versa

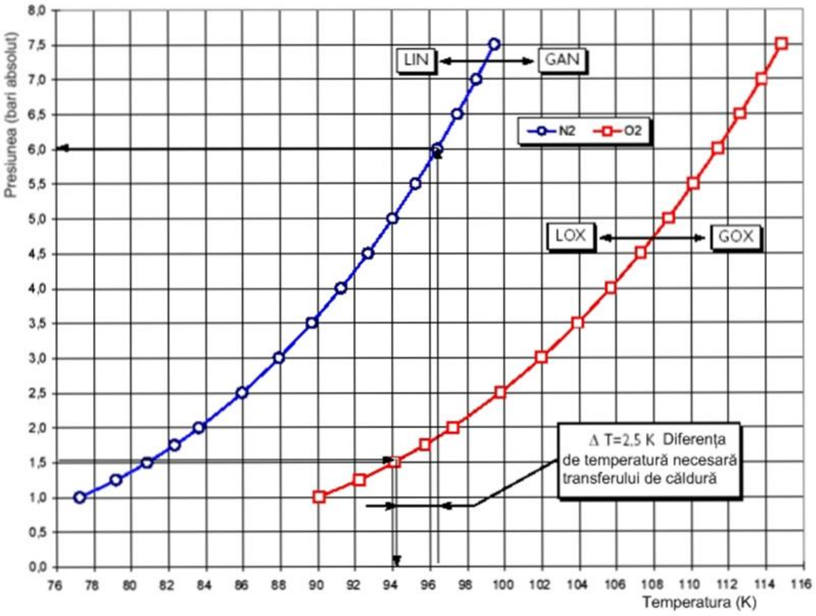


Figure 3.2. Liquid-vapor saturation curves for nitrogen and oxygen – pressure influence

Chapter III presents a calculation model of an installation in the equivalent of 1,500 tpd oxygen, using the PRO II program (produced by Company SimSci/Escor).

It is important to note:

Cryogenic air separation units (ASU) are typically subject to significant production variations, depending on:

- electricity and the conditions under which it is available – specific to the systems where the "plant load dynamics – Energy cost management" is practiced.
- dynamics of internal production orders/requirements or from the external market (liquid based mainly)
- planned / emergency maintenance programs of the installation

This principle - "plant load dynamics" considers the operation of the systems indifferent loading conditions of the factory, depending on the electricity tariff: day-night tariff or work-day tariff vs. weekend tariff. For example, the production of cryogenic liquids can be achieved under lower tariff conditions (e.g. at night) using in this way the obvious advantages, which in the end lead to an increase in the operational profit.

It follows that the sensitivity/limits of the production system must betaken into account in order to evaluate the operating conditions of the ASU in different production scenarios.

CHAPTER IV

Mathematical model, in stationary conditions, of the distillation zone of a cryogenic air separation installation.

The mathematical model in stationary regime is essential for the conceptualization, design and evaluation of processes. However, the stationary (equilibrium) regime is an idealistic definition used by engineers as a representation of the "design" conditions that are not always valid due to the quantitative and qualitative modification of the raw materials availability and final products condition, the change in the capacity of the installation due to the operating conditions, the marketing requirements, and the dynamic behavior inherent in the consumption processes.

Like a stationary model, dynamic models are based on universally valid principles:

Conservation laws, phase balance, heat and mass transfer and kinetics are also applied in dynamic models.

The calculation of the air separation installation was made considering two variants - the distillation area considered as having columns with plates and then columns with filling packages. For the columns with trays, the distillation process is done in increments (on the plates inserted on the height of the column), while in the columns with filling the distillation process is continuous, on the height of the column.

- **In the case of the trays / plates columns, the simplifying assumptions were:**

- 100% efficiency of the tray and the perfect contact between the vapor flow and the reflux of liquid on each step;
- Insignificant loss of heat on the tray;
- Constant pressure drop on each tray;
- Pressure and uniform temperature on each pan

The study performed on the cryogenic air separation installation revealed the following aspects:

1. Since the pressure at the top of the argon column is very low (1.2 bar), it is considered that argon is obtained only in liquid state. If the pressure in the Argon Column would allow the obtaining of argon in the vapor state, the advantage arises that nitrogen tracks can be purged through the upper part of the Argon Column;
2. For the control of argon production, it is required that variables for controlling the operation of the air separation installation, should consider at least 5 items:
    - The air supply flow of the high pressure Column (U_1);
    - The air supply flow of the low pressure Column (U_2);
    - The flow rate of liquid nitrogen extracted from the upper part of the high pressure Column and introduced into the low pressure Column (U_3);
    - Residual nitrogen flow (U_4);

- The fluid flow rate extracted from low pressure Column and introduced into Crude Argon Column (U_5).

3. An additional option that can ensure a high degree of argon recovery is the regulation of the oxygen flow extracted from the low pressure Column, so as to influence the location of the vapor flow with maximum concentration in argon next to the connection for the extraction of the supply flow of the Crude Argon Column (Argon transition flow).

- **In the case of Columns with filled packages, the simplifying hypotheses were:**

1. The mass flows at the vapor diffusion are given by Egoshi's correlation;
2. Sensitive vapor heat flows shall be estimated with a relationship similar to that used for their diffusion;
3. Convective mass fluxes are estimated by a mass balance at the liquid-vapor interface;
4. The diffusion flows for the liquid phase and the sensitive heat streams are calculated on the basis of the penetration model;
5. The contact surface for heat transfer and mass is equal to the apparent surface of the filling package;
6. The surface temperatures of the liquid are equal to the boiling temperatures.

Figure 4.20 shows the physical model of heat and mass transfer in case of distillation

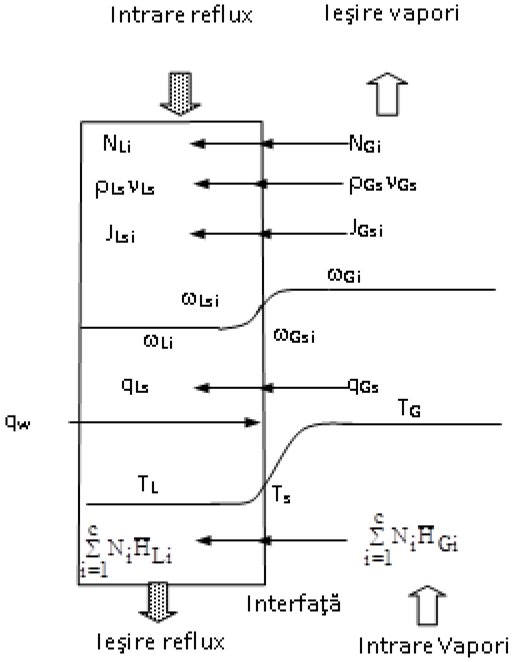


Figura 4.20. Modelul fizic de transfer de căldură şi masă în distilarea unui amestec tricomponent

In order to validate the presented model, a comparison of the variation of the concentrations obtained by calculation with experimental data was made, on a pilot installation of air separation, in classical configuration – a process similar to the process indicated in figure 4.1, whose operating data are indicated in Table 4.4.

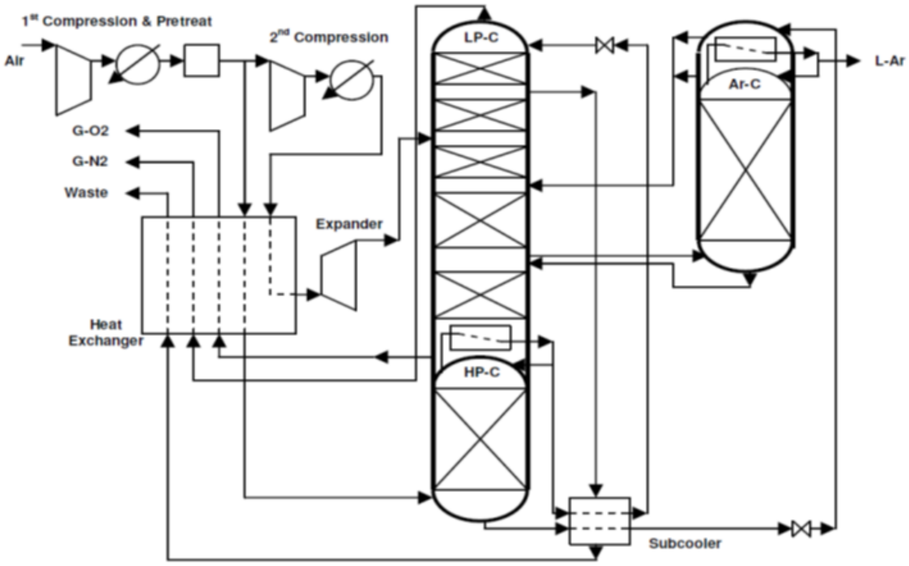


Figura 4.1. The scheme of the cryogenic air separation installation, with argon production

Tabel 4.4. Condiţiile de operare în testele T1 si T2

	Test T1	Test T2
Alimentare coloană înaltă presiune, [mol/s]	37.12	53.12
Produs azot, [mol/s]	21.68	30.66
Produs oxigen, [mol/s]	7.61	10.88
Produs argon, [mol/s]	0.31	0.43
Re_{Gef} în coloana de joasă presiune	6130-8080	8620-12090
Re_{Gef} în coloană de argon	5360-6350	7860-8080

The chapter therefore presents a method of modeling the distillation of multicomponent mixtures, a model verified with the data obtained on a pilot air separation installation. The model can be applied to distillation columns filled with packages by considering the interaction between diffusion streams.

This model is an alternative to the theoretical model made using the HEPT method (the equivalent height of the theoretical tray), especially in the case of the analysis of the separation of oxygen-argon in the Crude Argon Column.

The theoretical results obtained by the diffusion flow method are much closer to those obtained experimentally, compared to the results obtained by the HEPT method.

The method of diffusion flows allows an analysis of the location of the connections for the introduction and extraction of the material flows in the distillation columns, especially in the case of the Low Pressure Column.

CAPITOL V

5.A. Possibilities to improve the energy efficiency of the distillation zone of a cryogenic air separation unit.

5.B. Comparative experimental study.

5.A. In an attempt to achieve a process that can significantly decrease the energy consumption of conventional air separation installations by cryogenic methods, there are several major study directions:

1. Improving the performance of the Condenser-Evaporator that cover the thermal coupling of the Low Pressure Column with the High Pressure Column.
1. Replacement of the double rectification column with a single column, in which the Condenser - Evaporator is located at the bottom.
2. Replacement of the double distillation column with a thermally integrated column (HID$_I$C), in which, the Low Pressure Column is introduced into the High-Pressure Column (the nitrogen-oxygen heat exchange is distributed practically over the entire height of the column).

All these directions aim at a minimization of the temperature difference between liquid oxygen and gaseous nitrogen, a maximization of the heat exchange surface between these fluids.
The increase of the Condenser-Evaporator performances requires in particular the improvement of the film flowing of the liquid. The key elements that influence this type of flowing are:

- Control of the minimum flow of liquid that vaporizes at the exit of the heat transfer area;
- Design of the liquid distribution system on the heat exchange surface;
- The minimum liquid flow rate, which depends on the type of heat exchanger, the type of boiling surface and the type of flow distributor used.

The second direction of improving the energy efficiency, which involves the replacement of the double distillation column with a simple column, requires the compression of the nitrogen obtained at the top of the column to a pressure that ensures the heat exchange in the condenser-evaporator located at the bottom of the column.

This study solution is radical, since it completely transforms the principle of distillation into a double column.

To analyse the potential energy savings of an HIDiC, both concepts must be considered - that of the partial distillation column and, respectively, the ideally thermally integrated.

Although HIDiC is an energy-efficient distillation technology, it presents great difficulties in achieving an efficient configuration in practice, therefore, a high-performance equipment design is the key to its industrial implementation.

5.B. With practical valences in terms of improving the performance of an air separation installation, a comparative study was carried out between two medium / high capacity industrial installations, installations whose main parameters are indicated in Table 5.B.1.

	Coef. Energ	Plant 1				Plant 2			
		Nm3/h	bara	grdK	grdC	Nm3/h	bara	grdK	grdC
Process Air		320,000	5.75	291	17.85	201,441	12.6	301	28
Oxygen gas I		44,000	26	289	15.85	37,966	25.1		-273
Oxygen gas II	0.4	17,900	1.05	287	13.85				
Liquid Oxygen	1	2,000	1.4	90	-183.15	3,972	1.4		-273
Nitrogen gas I	0.21	28,000	21	289	15.85				
Liquid Nitrogen	0.93	3,000	1.1	78	-195.15	5,712	1.2	78.5	-194.5
Argon gas	0.65	500	21	280	6.85				
Liquid Argon	0.85	1,260	1.1	88.9	-184.25	1,740	1.7	92.46	-180.54
Total extracted Argon		1,760				1,740			
Consumed Power, Kw		**38,645**				**28,215**			

Table 5.B.1. Main operating parameters

Following the measurements taken and the energy analysis, the performances of the two installations can be summarized in the table (5.B.3.) below:

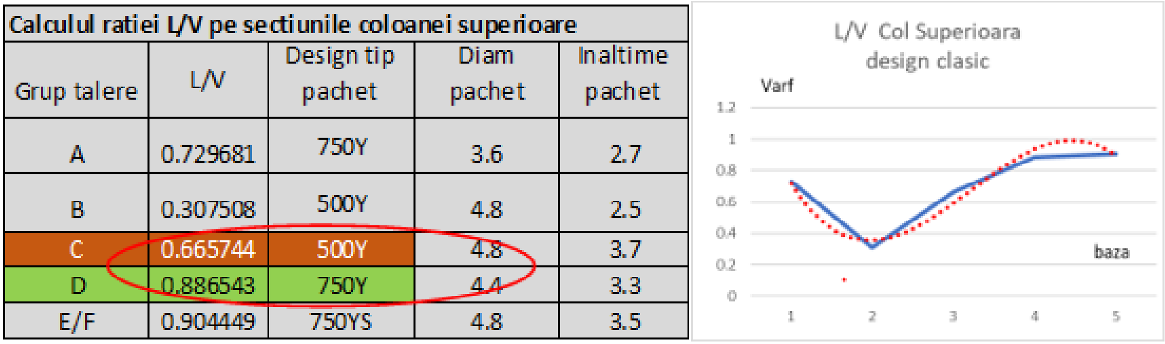
		Plant 1		Plant 2	
	Consumed Power, Kw	**38,645**		**28,215**	
	Energy allocation Kwh/h				
	Liquids	***5,861***		***10,763***	
	Oxygen gas II- only separation energy	***7,160***		***0***	
	other streams/ internal compression	***325***		***0***	
	Oxygen gas I/ balance of allocated energy	**25,299**		**17,452**	
	Specific consumption, Kwh/ Nm3 Oxigen gas I	**0.575**		**0.460**	
		100.00%		**79.94%**	
Aer proces vs Oxigen	Factor theoretic, Nm3/aer vs Nm3/oxygen	4.774			
	Factor real, Nm3/aer vs Nm3/oxygen	5.01	104.90%	4.80	100.61%
	Coeficient real- oxygen recovery	95.33%		99.39%	
Aer proces vs Argon	Factor theoretic, Nm3/aer vs Nm3/argon	107.066			
	Factor real, Nm3/aer vs Nm3/argon	181.82	169.82%	115.79	108.15%
	Coeficient real- oxygen argon	58.89%		92.47%	

Preliminary conclusions to be drawn from Table 5.B.3. are the following:

1. Both installations have an oxygen recovery coefficient above 95%, the threshold above which oxygen recovery is considered to be very good.
2. Plant 2 has an extraordinary argon recovery coefficient (usually there are units with optimal efficiency when separating argon between 80-85%)
3. For Installation 2, the specific consumption expressed in "Kwh/Nm3 Oxygen gas I" is about 20% lower than that of Installation 1.

For the two installations, it was subsequently analyzed at the detailed level the functioning of the Lower Column/ Main Condenser/ Upper Column/ Gross Argon Column/ Raw Argon Column Condenser, mentioning/calculating the main operating parameters (including the thermal loads of the mentioned heat exchangers) and then it was concluded on:

The major influence it exerts on the loading of the Upper Column (of the groups of filling-type rectification packages), the extraction of the argon fraction (vapor state) and the return of liquid oxygen as a product of condensation and rectification in the Crude Argon Column. Consequently, the column builders proceeded to an optimization between the right choice regarding the density of the packaged plates used (the range 750 vs. the 500 range) and also their diameter (closely related to the dynamic loading of the column) vs. the height of the packets (in line with the theoretic number of trays required).



Calculul ratiei L/V pe sectiunile coloanei superioare				
Grup talere	L/V	Design tip pachet	Diam pachet	Inaltime pachet
A	0.729681	750Y	3.6	2.7
B	0.307508	500Y	4.8	2.5
C	0.665744	500Y	4.8	3.7
D	0.886543	750Y	4.4	3.3
E/F	0.904449	750YS	4.8	3.5

Figura 5.B.20.- ratia L/V Coloana Superioara.

Regarding the Upper Column – Installation 1, at the same constructive density as the packaged trays groups E and F (surface/volume ratio of the packages type 750) the group of trays D is characterized by a smaller required diameter due, as calculated, to the different ratio (inverse) between the liquid flow and the vapor flow related to this section of the column. – Figure 5.B.20. and 5.B.21

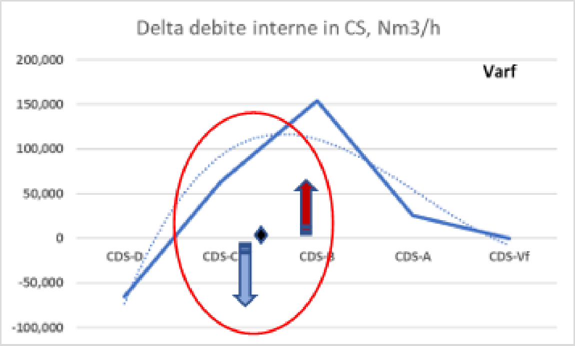


Figura 5.B.21. Inversiunea incarcarii pachetelor in Coloana Superioara

This reserved space in the Upper Column, in the area of the classical argon transition, creates the conditions for studying the opportunity of installing a first group of trays related to the Argon Column in the Upper Column, and this fact was analyzed on Installation 2- case study.

Instead of Conclusion:

The optimization of the processes in the air separation installations and especially the optimization of the processes in the separation columns was and remains a permanent theme. The appearance of high-performance rectification packages with extraordinary densities (m2/m3) and outstanding rectification performance has led to the important reduction of pressure losses in columns, with astounding benefits in optimizing energy consumption. We can also now discuss about obtaining extraordinary purities of the separated gases, directly from the Separation Columns, with impurities of ppb order.

The theme approached, and I would refer in particular to the combination of rectification processes in the Upper Columns with the processes in the Argon Columns, has extremely important implications in the dimensional optimization of the equipment.

In addition to the analyses directly related to the intimacy of the air separation processes, it is obviously necessary to continue the research related to:

- the requirements and advantages of optimizations in the area of working pressures,
- investigation of new methods regarding the thermal integration of equipment
- defining clear algorithms that allow the operation of an installation as close as possible to the customer's consumption profile, etc...

We have also seen the importance that derives from the fact that not only the processes and their optimization lead to the reduction of operating costs, but also a series of optimizations in the constructive area such as the decrease in the height of coldbox-es can have an extremely important impact in the same direction.

It is necessary to continue the studies/ researches in order to standardize the solutions and I would also mention the importance of a sensitivity analysis of the processes in the Crude Argon Column in line with the pressure variation in the Upper Column, which determines the increase of the nitrogen content in the transition flow.

The challenge comes from the fact that regaining the stability of the processes in the area of the Upper Column can be done relatively quickly, while the resumption of argon production requires time intervals of 1-2 days, depending on how critical the aforementioned disturbance was.