

A DISSERTATION ON

**EVALUATION OF ENERGETIC AND EXERGETIC
PERFORMANCE OF A CRYOGENIC AIR SEPARATION
PLANT FOR GENERATING LIQUID OXYGEN : A CASE
STUDY**

Submitted in partial fulfillment of the requirement
for the award of the degree of

Master of Technology

In

Thermal Engineering

Submitted By

SAJAL GUPTA

Roll No.2K14/THE/20

Under the guidance of

DR. RAJESH KUMAR

Associate Professor

Mechanical Engineering Department



**DEPARTMENT OF MECHANICAL, PRODUCTION AND
AUTOMOBILE ENGINEERING**

DELHI TECHNOLOGICAL UNIVERSITY, DELHI

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DECLARATION

I hereby declare that the work, which is being presented in this dissertation, entitled **“Evaluation of Energetic and Exergetic Performance of a Cryogenic Air Separation Plant for Generating Liquid Oxygen : A Case Study”** towards the partial fulfillment of the requirements for the award of the degree of Master of Engineering with specialization in Thermal Engineering, from Delhi technological University Delhi, is an authentic record of my own work carried out under the supervision of **DR. RAJESH KUMAR** Associate Professor, Department Mechanical Engineering, at Delhi Technological University, Delhi.

The matter embodied in this dissertation report has not been submitted by me for the award of any other degree.

Sajal Gupta

2K14/THE/20

Place: Delhi

Date: 29/06/2016

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

DR. RAJESH KUMAR

Associate Professor

Department of Mechanical Engineering

Delhi Technological University

Delhi-110042

CERTIFICATE

It is certified that Sajal Gupta, Roll no. 2K14/THE/20, student of M.Tech. Thermal Engineering, Delhi Technological University, has submitted the dissertation titled **“Evaluation of Energetic and Exergetic Performance of a Cryogenic Air Separation Plant for generating Liquid Oxygen : A Case Study”** under my guidance towards the partial fulfillment of the requirements for the award of the degree of Master of Technology.

He has calculated the energy and exergy analysis of the air separation plant using EES and Refprop software. His work is found to be satisfactory and his discipline impeccable during the course of the project. His enthusiasm, attitude towards the project is appreciated.

I wish him success in all his endeavors.

DR RAJESH KUMAR

Associate Professor

Department of Mechanical Engineering

Delhi Technological University

Delhi-110042

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Sajal Gupta

2K14/THE/20

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LIST OF SYMBOLS/ABBREVIATIONS

h	Specific enthalpy in KJ/Kg
T	Temperature in °C
ω	Specific humidity in kg/kg of dry air
P	Gauge pressure in bar
\dot{m}	Mass flow rate in kg/sec
ϕ	Relative humidity of moist air
\dot{V}	Volume flow rate of air in m ³ /hr
\dot{Q}	Heat transfer in KW
\dot{W}	Work transfer in KW
η	Efficiency
\dot{E}	Energy transfer in KW
EIP	Energy improvement potential
β	Relative energy loss
$E_{L,k}$	Energy loss in KW
T_0	Ambient Environment Temperature in kelvin
$\dot{E}x_w$	Rate of exergy transfer due to work in KW
$\dot{E}x_0$	Rate of Output Exergy in KW
$\dot{E}x_i$	Rate of input Exergy in KW
$\dot{E}x_D$	Exergy Destruction Rate in KW
ψ	Exergy efficiency
ExIP	Exergetic Improvement Potential
α	Exergy loss in KW
σ	Entropy generation in KW/K

Subscript

HE Heat Exchanger

Comp Compressor

cold Cold fluid

o outlet

i inlet

w Water

CHAPTER 1: INTRODUCTION

1.1 Background:

In all over world there are 3000 air separation plants in almost 80 countries. Recent development has been taken place in last 15 years. The brief history of air separation is as follows:

- World's first commercial liquefaction plant was built in 1895.
- In 1902 world's first air separation plants was built for oxygen production.
- In 1910 world's first air separation plant was built using double column rectification process.
- In 1954 first time the air separation plant was built by means of absorbers.
- In 1970 the first computer control was used in air separation plant.
- In 1984 World's largest VAROX plant was built which has the capability of adjustment with variable oxygen demand.
- In 1991 world's largest air separation plant using packed columns was built.
- In 1992 Air separation plants were built to produce gases with high purity.

1.2 Composition of Air:

The main constituents of air are nitrogen (78%) and Oxygen (21%). The Argon gas composition is 0.9%. The remaining 0.1% is made up of carbon di oxide, neon, xenon and krypton. These components can be separated from air by rectification process in a air separation unit.

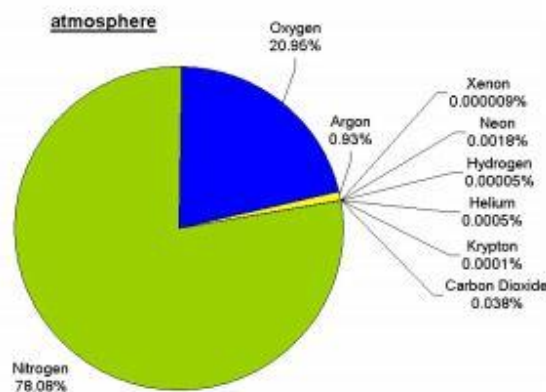


Fig. 1.1 : Composition of atmospheric air

Nitrogen, Oxygen and Argon are very important from chemical point of view in the present industries. These gases are used with high purity in chemical, steel, semiconductor, refining, aeronautical, medical industries and food processing.

Air if cooled down below its critical temperature becomes liquid then by the rectification process it is separated into its constituents. The main components which are separated by rectification column are nitrogen, oxygen and argon. An example of use of nitrogen and oxygen can be seen in Integrated Gassification Combined Cycle (IGCC) where oxygen is used in gassifier and nitrogen is fed to the turbine.

Demand of pure oxygen goes on increasing day by day. The oxygen is currently used in metal production, glass & concrete products, petroleum industry and oxy-acetylene welding. The medical market of oxygen is increasing at very high rate. Gaseous nitrogen is used in petroleum and chemical industries. Since nitrogen is inert gas hence it is used in electronics and metal industries liquid nitrogen is used in food freezing. Argon is also an inert gas so it is widely used in steelmaking, welding and in electronics industry.

The critical temperature of nitrogen and oxygen are as follows:

	Nitrogen	Oxygen
Normal Boiling Point, °K	126.1	154.4
Critical Pressure	34.6	51.3
Critical Temp, °K	773.35	90.19

Table.1.1 : Critical Temperature of Nitrogen and Oxygen

Cryogenics air separation process is generally used for the air separation. It is highly energy intensive process. Oxygen has the highest boiling point among three main components and is taken from the bottom of lower pressure column. Nitrogen is collected from the top of high pressure column. For the production of Argon, a separate distillation column is installed.

1.3 Low Temperature Achievement:

1.3.1 Joule-Thomson Effect:

In today's scenario most of the air separation processes use the J-T valve to achieve the low temperature. The flow through the J-T valve is irreversible process. The inlet and outlet conditions lie on same enthalpy curve. Isenthalpic expansion of a real gas on T-P diagram is divided into two regions by the inversion curve. On the one side of inversion curve if the pressure is decreased the temperature of real gas increases, while on the other side of inversion curve as we decrease the pressure its temperature also decreases. So while expanding the gas through J-T valve is must be keep in mind that the operating

condition should lie in the region where a net decrease in temperature occurs. Following figure show the T-P diagram of J-T expansion valve:

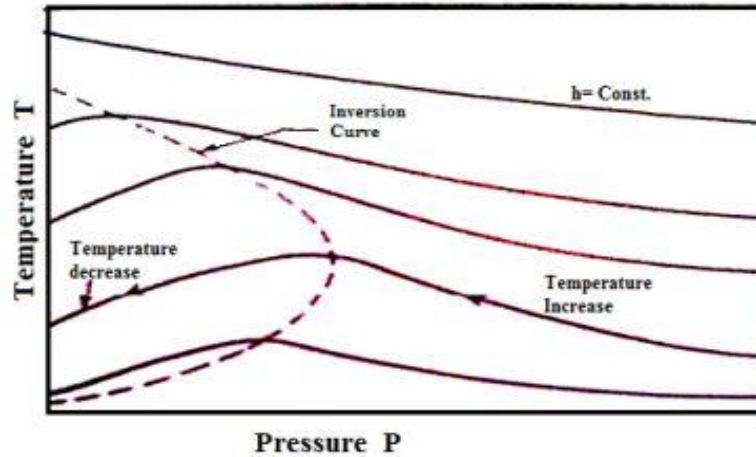


Fig.1.2 : Isenthalpic Expansion of real gases

1.3.2 Adiabatic Expansion:

The second method of achieving the lower temperature is by the adiabatic expansion through a work producing device, such as expansion engine. In the ideal condition the expansion will be reversible then the process will be adiabatic and isentropic

1.4 Air liquefaction Cycles:.

1.4.1 Ideal Liquefaction Cycle:

This process is ideal from thermodynamic point of view only. While practically it is not an ideal process. The ideal cycle in thermodynamics is considered as carnot cycle. The process starts with isothermal compression followed by adiabatic and isentropic expansion. The final condition is chosen at same pressure as inlet condition. The pressure after the compression process is very high and in the order of 70 to 80 Gpa for nitrogen. Since such a high pressure is not practical to achieve in isothermal compression, hence this process is not practically possible.

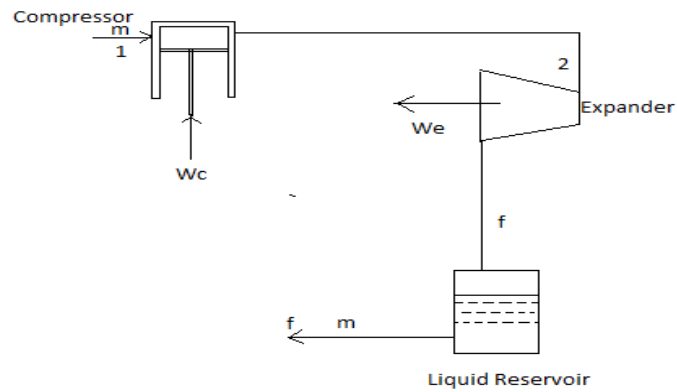


Fig.1.3 : Circuit Diagram of ideal Liquefaction cycle

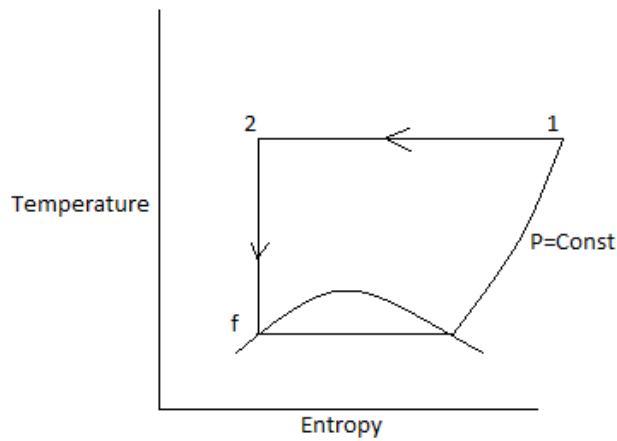


Fig.1.4 : T-s Diagram of ideal Liquefaction cycle

1.4.2 Linde- Hampson System:

The Linde-Hampson cycle is the simplest process for the air liquefaction. Joule-Thompson valve is used for the expansion of the air. The air is compressed from point 1 to point 2 isothermally in the compressor and sent to the regenerative heat exchanger where it exchanges the heat with the returning streams, which further cools the process air and the air comes at point 3. Then after the air is expanded through the J-T expansion valve from point 3 to point 4. At point 4 some of gaseous streams gets liquefied and is withdrawn at point f. The remaining gas leaves the liquid receiver at point g. This streams passes through heat exchanger, where it gets heated and then sent back to compressor after mixing it with make-up air.

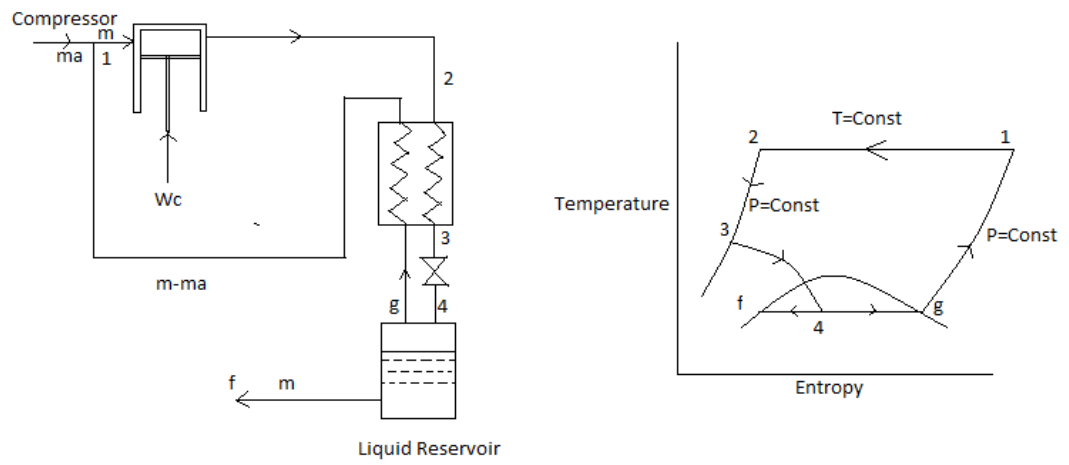


Fig.1.5 : Circuit diagram and T-s diagram of Linde-Hampson Cycle

CHAPTER 2 : LITERATURE REVIEW

L.V. van der Ham, S. Kjelstrup[1] evaluated two process design of air separation unit by exergy analysis. The air separation unit is part of an integrated gasification combined cycle, which supply oxygen to the gasifier and nitrogen to the gas turbine. The process are different from the point of view of no of distillation columns, rest of the specification are same in the two processes, either two or three. The Results shows that use of the third column, exergy destruction in the distillation section is reduced by 31%. The rational exergy efficiency, which is defined as the exergy change divided by the total exergy change; is found to be 38% in the three-column design and 35% in the two-column design. Almost 50% of the exergy destruction occurs in compressor and after-coolers. They also proposed to use the use of heat of compression for the preheating of air separating products or for the production of steam, which can be used in the steam turbine cycle.

R.L. Cornelissen-G.G. Hirs[2] performed an exergy analysis to analyses the possibilities of fuel saving in the cryogenics distillation process, which is the main method of air separation. The results shows that more than half of the exergy loss takes place in the liquefaction unit and almost one third in the air compression unit. Minor exergy losses are taking place in the distillation unit and the main heat exchanger. He also concluded that the major cause of exergy loss is the use of compressor and to a lesser extent the use of turbines.

S.N. Sapali, V. N. Raibhole [3] also performed the exergy analysis of air separation unit integrated with biomass gassifier. Since the air gassification produces the poor quality of syngas, oxygen is used as a gasifying agent for the gasification of biomass. He performed the simulation of the medium purity cryogenic air separation unit integrated with biomass gasifier. Simulation was performed on Aspen Plus. In his results it is found that Oxygen is obtained with the purity of 96.2 % mole basis with specific power consumptio of 0.2435 KW/scmh. Which is lower as compared to the traditional cryogenics air separation unit. Gaseous Nitrogen is produced at the rate of 734 scmh with purity of 99.9 %. The comprssor consumes the total power of 12.22 KW, which is compensated by the 9.32 KW power generated by expander.

Mathew Aneke, Meihong Wang[4] investigated the potential for improving energy efficiency of conventional ASU. They performed the simulation on Aspen Plus. Energy improvement is gained through converting the heat from the compressor, using organic Ranking cycle (ORC). Two different arrangements for utilizing the compressor heat in ORC systems were compared with te conventional cryogenic air separation unit. The conventional cryogenic ASU uses 3 stages of compression with intercooling. In the first arrangement the water which is used as a coolent in aftercooler and intercooler is replaced by R134a, which is also the working fluid for

ORC system. In the second arrangement, 3 stages of compressor of the conventional air separation unit is replaced by single stage compressor of overall same pressure ratio. The compressor effluent is cooled by R134a. The simulation results shows that the specific power consumption was 0.32 KWh/Kg, 0.37 KWh/Kg, 17.35 KWh/Kg of oxygen, nitrogen and argon respectively for conventional cryogenic air separation process. The specification power consumption is reduced by the addition of ORC system. The second arrangement of ORC system reduces the specification power consumption by 0.2 % , while the first arrangement of ORC system reduces the specific power consumption by 11 %. The total power consumption of the conventional cryogenic air separation unit was 21826.19 KW, which was also reduced in the same proportion.

Zeinab A. M. Khalel[5] , Ali A. Rabah & Taj Alasfia M.Barakat have also performed the exergy analysis of newly developed cryogenic ASU unit with flash separator. Conventional double column air separation process is used as a reference. Thermodynamic data are obtained by simulating the process on Aspen Plus. The results of the simulation shows that the exergy loss is reduced by 17.2 % in the modified process as compared to the reference process. The rational efficiency is found to be 16 % , while that of conventional process is found to be 12 % . The energy consumption of the modified process is 16 % lower than that of conventional process. Another advantage of this process was the production of oxygen and nitrogen with more purity as compared to conventional process.

Chao Fu and Truls Gunderseen[6] analysed the air separation units for oxy-combustion process to reduce the power consumption by the exergy analysis. Oxy combustion is a process to capture CO₂. In their research exergy analysis of air separation units was performed, which produces the O₂ with low purity of 95 % mol and at low pressure of 120 Kpa. The results shows that the maximum exergy loss has been taken place in compressor and distillation system which is 38.4% and 28.2% respectively. If the isentropic efficiency of air compressor is increased to 0.9 from 0.74 then the total power consumption will be reduced by 10%. If double reboilers are applied in lower pressure column then the power consumption will be decreased by 10%. Results also shows that the exergy loss in the reboiler/ condenser is very low (6.3%), that's why the power saving opportunity by developing the new heat exchangers is limited.

Masaaki Taniguchi, Hitoshi Asaoka[7], Toshiyuki Ayuhara performed the exergy analysis to find out the energy saving in a air separation plant. Air-separation plants are used most commonly in steel, chemistry and electronics industries, which requires a lot of energy. Exergy analysis was performed on a new process, developed by Shinko Air Water Cryoplant (SAC). The results show that the total energy consumption in this new process which uses a new single column rectification process, is 30% less than the conventional double column air separation process.

Li Yao, LigeTong, Yunfei Xie [8], Jianbiao Shen, Huazhi Li and Shiqi Li performed the detailed exergy analysis of an Air separation unit of capacity 40000 m³/hr situated in Tangshan

Tandsteel Gases Co.,Ltd. The results shows that the molal exergy of oxygen is the largest among the gaseous products, where as the molal exergy of argon among the liquid products is largest. Exergy value of liquid products are larger than gaseous product. Hence the efficiency of the plant can be enhanced by increasing the production of liquid products. Exergy values for gaseous oxygen and nitrogen are 2017.28 KW and 443.17 respectively, where as the exergy values of liquid nitrogen, oxygen and argon are 131.152 kW, 380.99 kW and 367.85 KW respectively.

Hanfei Tuo, Yanzhong Li[9] represents a ideal combined cycle for natural gas liquefaction and air separation. Exergy analysis and simulation were performed to analyse the process and to find out the effects of critical parameter such as flow rate ratio β on temperature difference, its distribution and exergy losses. The results shows that as β increases the temperature difference as well as exergy losses decreases. Exergy loss in the heat exchanger decreases to 2.17 kW from 9.87 kW, hence increasing the exergy efficiency from 68.2% to 88.1% as β increases from 0.5 to 2.0.

Yu Zhu, Xinggao Liu, and Zhiyong Zhou[10] established a optimizing model for cryogenic air separation with argon column. Optimization was done on the basis of external and internal thermal coupling, energy balance, phase balance and component material balance. The objective of the optimization process was to raise the potential of cryogenic ASU by increasing the oxygen extraction percentage. The results show that the oxygen production is increased by 29.65% as compared to original process. As the oxygen extraction percentage increases, the argon extraction percentage also increases and is improved by 44.13%.

Vaijanath N. Raibhole & S. N. Sapali[11] performed simulation and parametric Analysis of Cryogenic Oxygen Plant for Biomass Gasification. The simulation was performed by using Aspen plus for cryogenic air separation process for medium purity oxygen integrated with biomass gasifier. The plant produces the oxygen with purity of 96.2% mole. The specific power consumption was 0.2435 kW/scmh of oxygen. In the simulation process the performance parameters such as temperature, purity, power consumption and pressure are obtained. Similarly the parameters like heating value and syngas composition was also predicted in the simulation process. The effect of number of stages in Poor Liquid as well as number of stages on RL and their purity was analysed. Also the effect of oxygen flow and temperature of gasifier on syngas composition was analyzed.

Emin Acikkalp, Hasan Yamık, Necmettin Caner and Erol Acikkalp[12] performed an energy and exergy evaluation of Air separation facility. The air separation plant produces 250 tons of oxygen, nitrogen, and argon per day utilizing the principle of two columns. The analysis was performed with respect to first law and second law analysis of thermodynamics. Energy and exergy values at each point had been calculated first, then after the evaluation of whole system and its components were made. Total energy and exergy efficiency of the plant were 0.453 and 0.13 respectively. Total energy loss of the plant was found to be 4368.475 kW and exergy destruction was found to be 10535.875 kW. Energetic improvement and exergetic improvement

potential rate were found to be 2391.535 kw and 3800.485 kw respectively. entropy production in the whole system was found to be 35.347 kw/k.

B.J.Sonani, J.K. Ratnadhariya[13] evaluated energy saving opportunities in oxygen plant. Plant capacity was 80 m³/hr. Initially the energy consumption was 1.30 to 1.40 kwh/ m³, but the theories suggested that the energy required to produce this much amount of oxygen was 0.90 kwh/ m³. He investigated the energy saving opportunities in the components. The first problem he found with the compressor that the compressor was four stage compressor, outlet pressure of compressor should be maintained at 36 atm. Instead of 42 atm. The efficiency of the compressor was only 75%. Another problem he found out with expander that for ideal oxygen plant the temperature drop should be 60 K, but in the expander the actual temperature drop was 50 to 51 K. Heat loss in the cold box was also at high side. The effectiveness of heat exchangers were also very low. After improving all these parameters, the energy consumption was found to be 1.1-1.2 kwh/ m³, resulting in overall saving of 14-15%. Financially 5 lacks rupees per annum can be saved.

Pyeong Soon Yong, Hung Man Moon and Sung Chul Yi[14] performed the exergy analysis of cryogenics air separation process for generating nitrogen. A cryogenic separation plant generating nitrogen has different configurations as compared to that of oxygen. In this paper a cold heat supply method and distillation column method was compared. The result shows that the exergy efficiency increases if we use the liquid nitrogen as cold heat source. In the distillation column method, the structural packing method gives the better exergy efficiency.

Marc A. Rosen, Ibrahim Dincer[15] analysed the Effect of varying dead-state properties on energy and exergy analyses of thermal systems. The study shows the effects of dead state properties variations on the energy and exergy analysis. These effects are studied for a coal fired power plant generating the electricity. The result shows that the sensitivities of the exergy and energy values and results of exergy and energy analysis to reasonable variations in dead state properties are sufficiently small. It has been concluded that although the exergy and the energy values are dependent on the properties at dead state, the results of exergy and energy analysis are usually not very sensitive to variations in these properties.

Yu Zhu, Sean Legg, Carl D. Laird[16] designed cryogenic columns under uncertainty by using multiscenario approach considering two classes of uncertainty. Process variable describes the uncertainty which is measurable during the operation and to compensate this uncertainty control variables can be used. This approach allows for the more efficient designs by considering the potential for operational changes in control variables. This method includes 196 scenarios and 675000 variables. Standard dextop solved this problem in 20 mins. This work uses a steady-state model and assumes perfect control is possible. Given the potential control challenges with such a highly integrated process, these optimization formulations should consider integrated design and control.

Harry C [17] developed a new cryogenic air separation technology, which complements traditional double column cryogenic air separation process. This process designated as moderate pressure (M-plant cycle), focuses upon recovery of argon and generation of moderate pressure nitrogen. This M-plant cycle produces argon and high purity nitrogen at about 200 Kpa pressure with very high purity oxygen above atmospheric pressure. This M-plant cycles conserves the pressure energy and results in physically smaller upper column size. Nitrogen piping size also reduces resulting in the cost saving . by this process nitrogen is produces at 200 Kpa and above can be saved up to 10% energy savings and 5% more argon recovery over traditional double column plant.

A.R. Smith, J. Klosek[18] reviewed the air separation technologies and integration with energy conversion processes. The author described the process for separating the gases from air for industrial purposes and considered the economic and other limits for each process. This integration of cryogenic and non cryogenics processes are described to use the gas turbine large amounts of excess heat available to be used as byproduct. The process having these characteristics is oxygen-blowdown, partial oxydation and Fisher-Tropsch plants.

D Nagarathinam[19] analysed the Heylandt cycle for the quality of liquefied air in the lower distillation column of the double rectification system. He described the enthalpy and the quality of liquefied air when it enters into the bottom of lower column. The whole system is enclosed in a cold box. He analysed the various parameters of Heylandt cycle. He optimised the the mass flow rate through expansion engine by its thermodynamic analysis. Result also shows the variations in the fraction of liquid and vapour in the lower distillation column for different intermediate pressures.

CHAPTER 3: AIR SEPERATION TECHNIQUES & DISTILLATION PRINCIPLES

An air separation plants separates the air into its main constituents i.e in Nitrogen and oxygen and also in argon and other components if required. The Air separation plants are available in different forms depending on what type of products are to be produced and in which form, the capacity of plant and the purity of component required. Then the process which has the lowest energy requirement as well as optimized cost is selected.

For any physical plant to run in a successful manner, the sizing and selection of components along with the proper selection of process, is always a combination of observation, experience and analytical modeling. The air separation process needs a very good integration between the heat exchangers involved in the process and the distillation column to achieve a very good efficiency. All the required energy for cryogenics refrigeration is provided to air by the compressor only.

3.1 Air Separation Techniques:

The various techniques to separate the air into its components are as follows:

1. Membrane Separation
2. Pressure Swing Absorption (PSA)
3. Vacuum Pressure Swing Absorption (VPSA)
4. Cryogenics Distillation

3.1.1 Membrane Separation:

Membrane seperation process separates the nitrogen from air by the concept of permeation across a membrane. The membrane used for the separation purpose consists of bundle of permeable hollow fibers. The gases like oxygen, carbon di oxide and water vapors permeate through the membrane very fastly as compared to the nitrogen which permeates through it very slowly.

Membrane process separates the air in to the two different streams. The one which is called the permeate consist of oxygen, carbon dioxide and water vapors. The another streams which is called the product stream consist of high pressure nitrogen. The nitrogen exits the downstream

and delivered to the end customer or to a compressor system if further compression is required. The another stream, permeate is vented to the atmosphere.

In this process we can control the purity of nitrogen in the down streams. It is done by changing the operating conditions. If the flow rate of nitrogen increase, its purity decreases. If the flow rate of nitrogen decreases, its purity will increase. To control the purity of nitrogen a flow control valve, flow meter and nitrogen analyzer are installed in the downstream i.e. at the nitrogen exit of membrane separation.

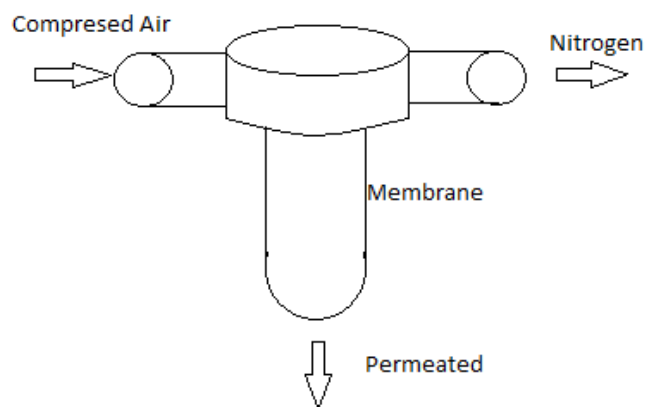


Fig.3.1 : Membrane separation process

The advantages are as follows:

- a) The process is economical for low flow rates.
- b) The calculation and design involved in the process is simple and easily understandable.
- c) Repairs and maintenance of the process is simple and low.
- d) Very few equipments are required for starting the process.

The disadvantage of the above process is that this process is not suitable where the very good nitrogen purity is required.

3.1.2 Pressure Swing Absorption:

Pressure swing absorption is a very useful technique used to separate a gas from a mixture of gases like atmospheric air. In this process the gas is separated under pressure and according to the molecular characteristics and the affinity of the required gas to absorbent. Since this process operates at ambient temperature that's why it is different from cryogenic air separation process.

In this process generally an absorptive material like zeolite is used in a molecular sieve. The absorptive material absorbs the gas according to the affinity of the gases at high pressure and then the system swings to the low pressure to desorb the gases and to be used as end products. This process is based on the fact that at high pressure the gases are attracted to the solid surfaces. Higher the pressure in the molecular sieve, more gas will be attracted to the solid surface based on its affinity. When the pressure is released the gas is also desorbed or released from the absorbent.

When the air is passed through the molecular sieve under pressure containing absorbent bed of zeolite, the nitrogen will be strongly attracted to zeolite as compared to oxygen. Almost all the nitrogen is absorbed by the bed and the streams at the exit of molecular sieve will be rich in the oxygen. When the bed is completely exhausted to absorb any further nitrogen, it is regenerated by releasing the pressure. At this time it will again ready to absorb the nitrogen in another cycle.

For the continuous production of gas two absorbent beds are used . At the same time one vessels absorbs the gas and the another vessels gets regenerated. The another advantage of using double bed absorption system is that the gas leaving the vessel being de-pressurized is used to pressurize the another vessel partially. This saves the lot of energy and is generally a common practice in the industries.

The advantages of the process are as follows:

- a) The process is very economical if the quantity of nitrogen is less than 20000 cubic feet per hour.
- b) The unit can be erected on site , which makes the nitrogen available if required.
- c) PSA units are easily available and can be delivered quickly.

If the flow rate of nitrogen is more than 40000 cubic feet per hour then it will be more economical to purchase the nitrogen from cryogenics units rather than setting up own set-up. Besides it the process is extremely noisy as compared to another process.

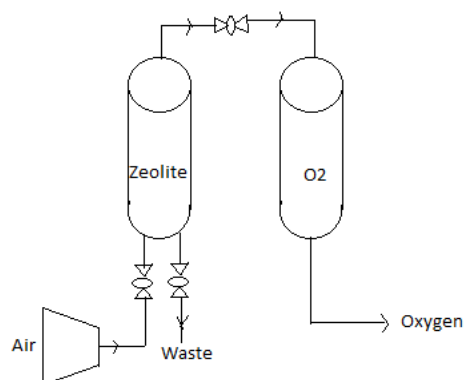


Fig.3.2 : Pressure swing absorption Proces

3.1.3 Vacuum Pressure Swing Adsorption:

The vacuum pressure swing adsorption is a variation of pressure swing adsorption system. In this process the blower is used instead of compressor to circulate the air to the system. The product stream is collected by using a vacuum blower at the exit. The use of blower decreases the amount of energy needed in system. These type of systems are effective only for plants which produces the oxygen in large quantities.

Comparison of Vacuum pressure swing adsorption with pressure swing adsorption and cryogenic separation process are as follows;

- Vacuum Pressure Swing Adsorption system are costly as compared to Pressure adsorption system but the energy saving in VPSA is more as compared to PSA system.
- VPSA system for oxygen production is economical as compared to PSA system for production of oxygen only when the production of oxygen is more than 20 tons per day.
- The purity of oxygen in VPSA system is not good enough. In that condition cryogenics air separation is used for the production of oxygen.
- VPSA specific power consumption for oxygen production is approximately 1/3rd of PSA plants used for oxygen production, but almost same to that of cryogenics air separation.

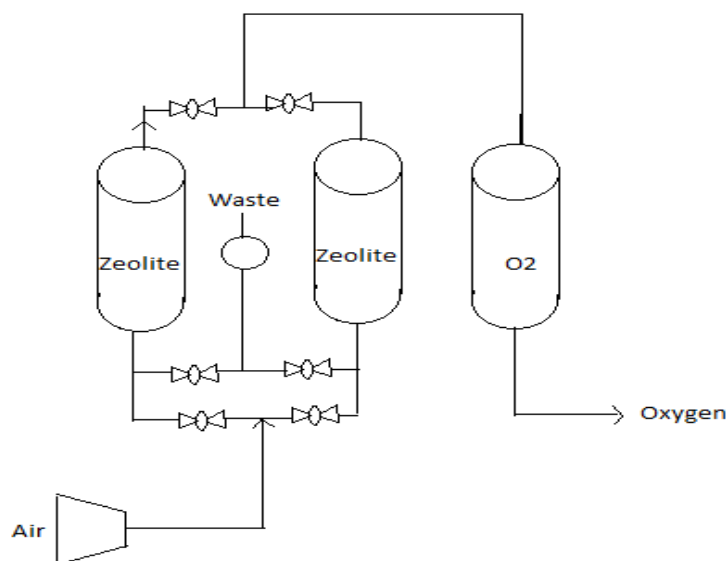


Fig.3.3 : Vacuum Pressure swing adsorption Process

3.1.4 Cryogenics Distillation:

Where we require the high purity oxygen, nitrogen and argon, cryogenics distillation is the best process. The only viable option for producing the neon, krypton and xenon is the cryogenics air separation process only. The process is used to built the nitrogen, oxygen and argon in liquid as well as gaseous phase. The gases are seperated because of different vapor pressure in atmospheric air. The general description of process is as below:

- a) Air is compressed in air compressor to sufficient pressure so that it can go through the system.
- b) Water vapor, carbon di oxide and oil droplets are removed by molecular sieve.
- c) The air is further cooled down in a series of heat exchanger by incoming streams from cold box.
- d) The air then passes through the expansion engine.
- e) After the expansion engine the air passes through distillation column, where the different streams gets seperated.

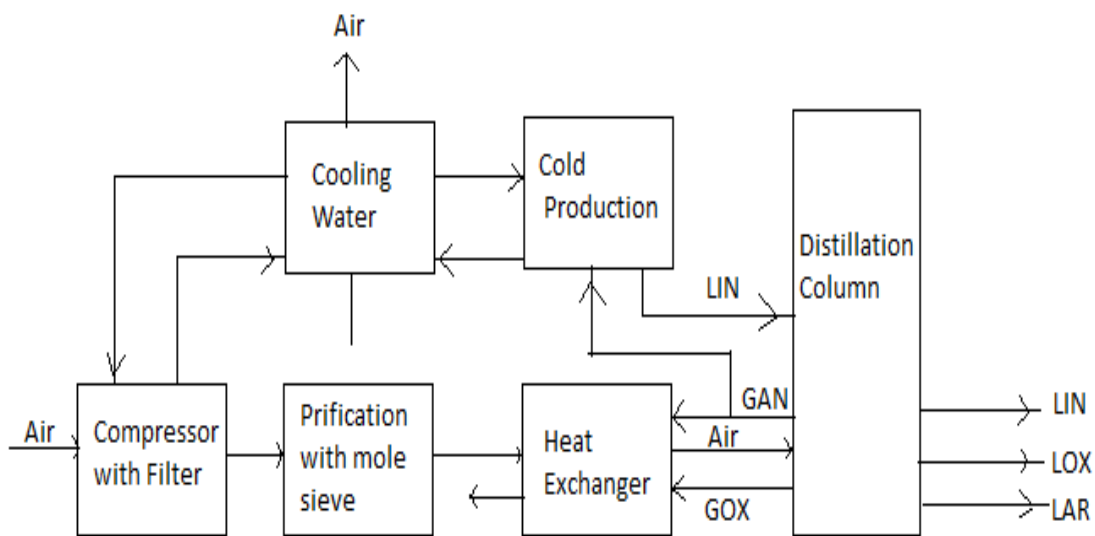


Fig.3.4 : Cryogenic Distillation Process

3.2 Comparison between different air separation process:

Process	Advantage	Disadvantage
Cryogenic	<ol style="list-style-type: none">1. Lower electricity per unit of nitrogen.2. Produce high purity of nitrogen and oxygen3. Liquid nitrogen can be generated for storage on site	<ol style="list-style-type: none">1. Requirement of larger space.2. Start-up and shutdown periods are larger.
PSA	<ol style="list-style-type: none">1. Capital cost is from low to moderate.2. High purity nitrogen at lower cost3. Start-up and installation period is small as compared to cryogenics.	<ol style="list-style-type: none">1. Required high maintenance.2. Noisy operation.
Membrane	<ol style="list-style-type: none">1. Capital cost is lowest among all process.2. Output is flexible in terms of production capacity.3. Quick installation and start up.	<ol style="list-style-type: none">1. Not economical for high purity requirement.2. Not economical for large outputs.3. Electricity requirement is relatively high.

Table 3.1 : Comparison between different air separation process

3.3 Distillation Principles:

To separate the air into its constituents by rectification the air must be liquified. By the thermodynamic property chart it is clear that a gas can be liquified only when its temperature and pressure is below that of critical point. The critical temperature of air is -140.7°C and critical pressure is 37.7 bar. Hence to liquified the air the temperature must be lower than -140.7°C . The following figure will illustrate the temperature and the pressure at which a gas condenses or evaporates:

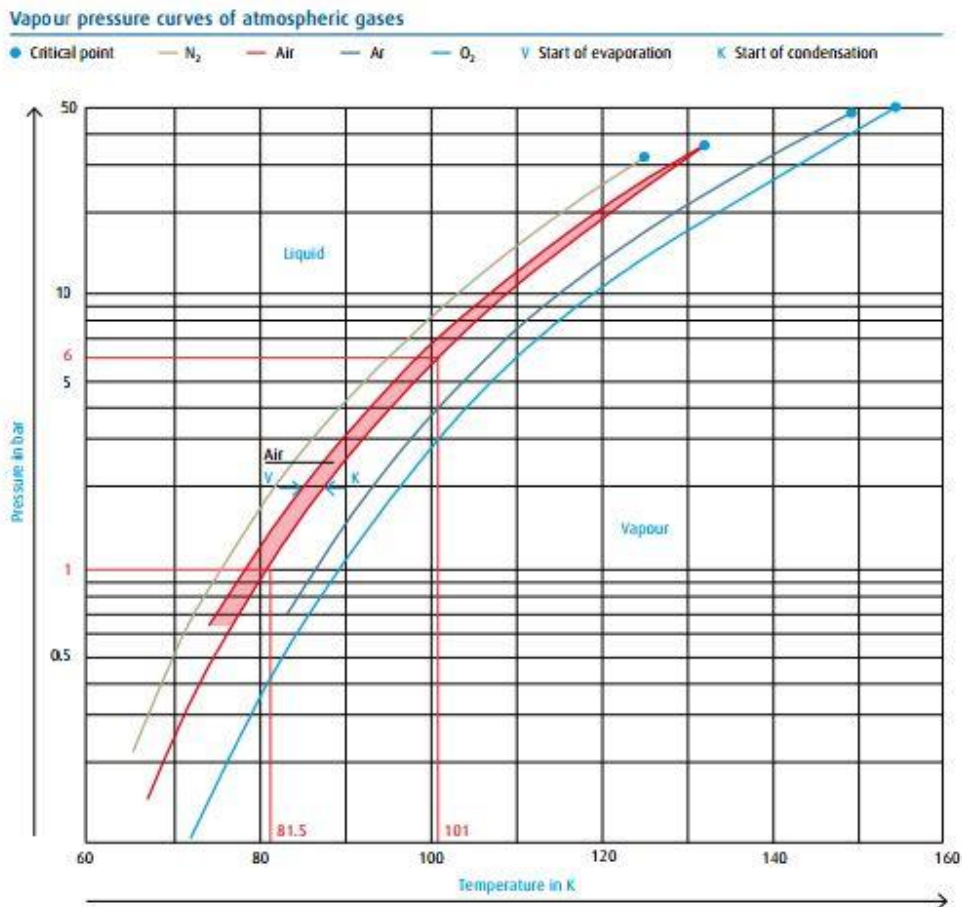


Fig.3.5 : Vapour Pressure Curve of atmospheric gases

From the following figure it is clear that the air can be chilled to -192°C before the condensation starts if the pressure is below atmospheric pressure. Similarly the air can be chilled upto -172°C before the condensation starts if pressure is below 6 bar.

Rectification is the countercurrent distillation process. Due to this special process air mixture can be separated into its components with high purity and a high yield of product, even when the boiling points of components are very close to each other.

Each component in air has different vapor pressure. Due to the difference in the vapor pressure the composition of liquid mixture and gaseous mixture of air differs from each other. The vapor pressure of nitrogen is greater than that of oxygen in air. Hence the vapor produced from boiling of liquid mixture of O₂/N₂ will have higher concentration of nitrogen than the liquid mixture which is boiling.

Similarly when the mixture of O₂/N₂ condensates, the liquid will have a higher concentration of O₂ because the partial pressure of O₂ is lower than that of N₂. The component having the lower partial pressure will tend to liquefy first.

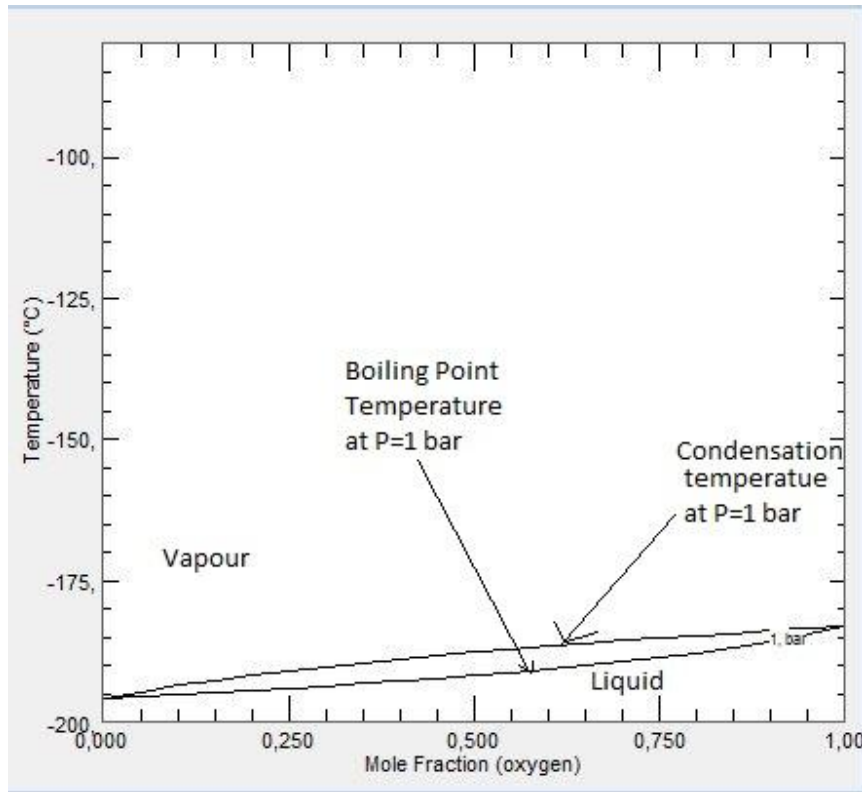


Fig.3.6 : Temperature-Composition diagram of Oxygen/Nitrogen Mixture at 1 bar pressure

Any tray in the distillation column follows the same principle. The O_2 concentration in boiling mixture of O_2/N_2 (denoted by F) is greater than O_2 concentration of Vapor mixture (denoted by D). When the reflux is fed into the column, the same amount of liquid flows down from the tray above into the liquid mixture just below with an equal volume flowing down on to the tray below. As shown in the figure when the vapor D_u interacts with the liquid mixture F and will have the higher concentration of O_2 as compared to D. The vapor D_o rising from the above tray will have the less concentration of O_2 as compared to D. Hence as we go from bottom tray to upper tray the concentration of N_2 goes on increasing in vapor mixture. Similarly the concentration of O_2 in the liquid mixture goes on decreasing as we move from lower tray to upper tray.

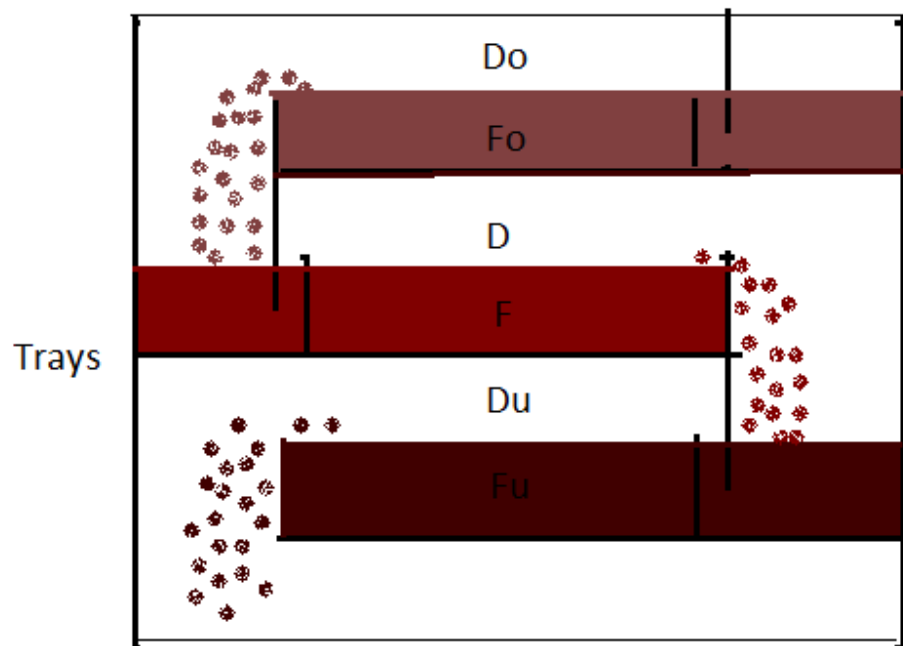


Fig.3.7 : Cryogenic distillation column tray showing interaction between Vapour and Liquid

CHAPTER 4 : SYSTEM COMPONENTS AND PPROCESS DESCRIPTION

Air is a mechanical mixture of oxygen, nitrogen and other gases and its physical properties lies sbetween the two but closer to those of nitrogen. In its normal atmospheric condition, air is colorless, odorless gas. Air which is normally in gaseous state can be liquefied as stream from gaseous state can be condensed to liquid state.

The plant manufactured by Cryogenics section of Bhartiya group of industries have normal operating pressure of 40 kg/cm² . This is achieved with the incorporation of Expansion Engine along with Joule-Thompsons expansion valve.

4.1 Layout of Plant-

Normal layout of the plant is as shown in the following figure:

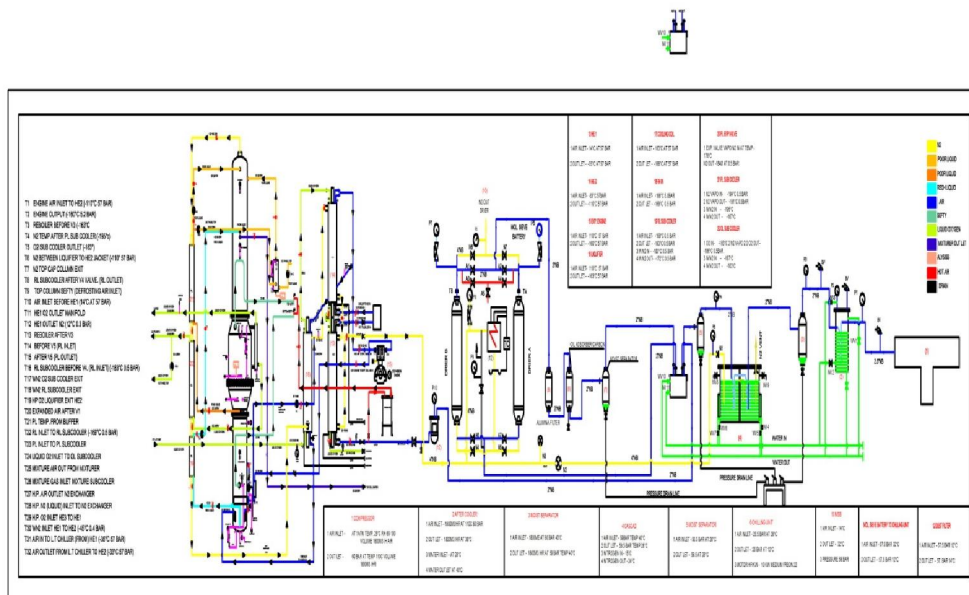


Fig.4.1 : Plant Layout of Cryogenic Air Separation Process

4.2 Block Diagram of Plant-

For the illustrative purpose the block diagram of the same layout is shown as below:

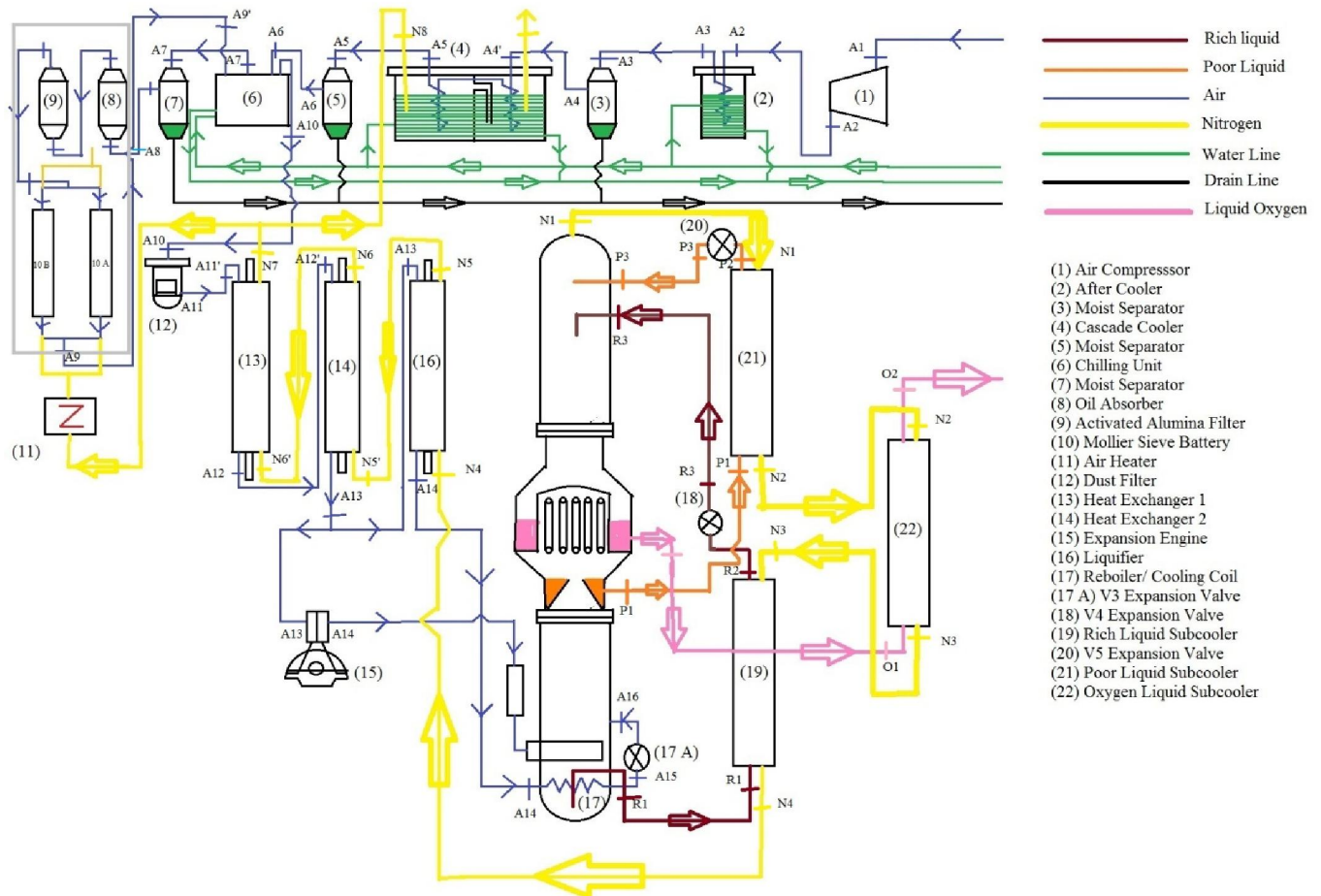


Fig.4.2 : Block Diagram of the plant layout

4.3 Liquid Oxygen Production Process-

The liquid oxygen is produced by the following steps :

1. Air is sucked into the Air Compressor through suction air filter where the dust particles are removed. The Air compressor is four stage reciprocating compressor with intercooler between the stages. The air is compressed upto 60 bar gauge pressure. Most of the moisture gets separated away in compressor while intercooling. The relative humidity at compressor end is maintained as 15 %.

2. The air is passed through the after-cooler after compression in compressor. In after-cooler the air is cooled with the help of water circulating in after-cooler. Since the air is cooled below the saturation temp of water vapor present in the air, some of the water vapors are condensed in the after-cooler, which are separated in the moist separator. The temp of air at the exit of after-cooler is 25°C and the air is 100% saturated at the exit of aftercooler.
3. After the after-cooler the moist air is passed through the cascade cooler. Cascade cooler is a type of evaporative cooler. This cooler is elliptical tank having two compartments. The waste nitrogen enter in the cascade cooler from one side and the moist air is passed through the coils in cascade cooler. The water is filled in cascade cooler upto some level. A nitrogen vent is provided between the two compartments. The reaction between the nitrogen and water is endothermic reaction so when the nitrogen enters in the second chamber some of the water is evaporated. The heat of evaporation comes from the surrounding water. That's why the temp of water in the cascade cooler decreases which further cools the air passing through the coil. The mixture of nitrogen and water vapors goes into the first chamber. Same process happens there also and the temperature of water decreases in this chamber also which reduces the temperature of air. The air is cooled below the saturation temperature of water vapor present in the moist air. Hence some of water gets condensed here also. The lubricant which is mixed in the air is also gets condensed here. The condensate is removed in the moist separator. This is drained once in an hour.
4. The air from this evaporative cooler passes into the chilling coil tank, which is having the chilled water at temperature of 6°C to 10°C. This chilling of water is being done with the help of chilling unit. The chilling unit uses R22 as a refrigerant. In the chilling tank coil the moisture entrapped in the air further gets condensed which is separated in the form of moisture from the moist separator and is drained once in half an hour. The separation of moisture is carried out in different stages so that the air entering in the molecular sieve has minimum vapor level. Better absorption of CO₂ can takes place in the molecular sieve battery, if the moisture content is low in the air.
5. The air is pass through carbon filter packed with Activated Carbon. Here the oil vapor carried over from air compressor will be removed. If this oil vapor is not removed sufficiently, due to the spent carbon or due to high temperature of process air, the oil vapor will damage the molecular sieves. To obtain a long life of molecular sieve ensure that carbon filter is well maintained. A sample of carbon beads must be taken out from carbon filter once in six months and should be checked.
6. The Air in the chilling unit should be between 6°C to 12°C for better adsorption of carbon di oxide in the molecular sieve. The chilled air is then passes through molecular sieve drier unit. This unit have two vessels when one is on line, the other is on reactivation. The regeneration cycle of drier is 8 to 10 hours approx. in the molecular sieve the water vapor and carbon di oxide gas are completely removed. The air is free from any impurities and water vapors.

7. The cooled dried air is then passed through Dust Filter. It is hard compressive ceramic filter where small dust particles are arrested.
8. The dust, moisture and oil free cooled air is passed finally into cold box which consists of Heat Exchanger 1 & 2, Liquefier, Expansion Engine, Rich Liquid Subcooler, Poor Liquid Subcooler and Oxygen Liquid subcooler.
9. The air is first passes through Heat Exchanger 1 & 2 where it is cooled upto -100 °C by incoming nitrogen.
10. After the Heat Exchanger 2 the Air is bifurcated into two streams. 40% of the mass flow rate passes through the liquefier and 60 % of the streams passes through the Expansion engine. The streams entering into the Expansion Engine enters at 59 bar pressure and expanded upto 5.2 bar pressure. Rest of the stream passes through the Liquefier where it gets liquefied by the incoming Nitrogen gas. This stream is further expanded in the expansion engine. Both the streams now enter in to the buffer vessel and then to the bottom portion of lower column.
11. As the Air enters the lower column, after the expansion engine and after the expansion valve, part of the air condenses into liquid and falls at bottom of the column. This liquid is called the “Rich Liquid” and having 35-40% oxygen and 60-65 % Nitrogen.
12. A part of air in this column evaporates and rises to the top of column touching the condenser which is lower than the lower column. As this air touches the condenser, it condenses into liquid on top of lower column. This liquid is generally 96% to 99% Nitrogen and being poor in oxygen is called the “Poor Liquid”. The pressure in the lower column is between 4.7 bar to 5.5 bar in normal operating condition. Final separation of the two traction is achieved in upper column. Both the Poor Liquid and Rich Liquid are carried into the upper column by two expansion valves and the pressure drops from 5 bar to 0.5 bar in the upper column. This Rich Liquid enters the middle of Upper Column and as it flows down Nitrogen evaporates and oxygen continues as liquid. The Poor Liquid enters the top of upper column and is flows down the column, it comes in contact with any evaporating oxygen and condenses the same into liquid, while Nitrogen itself becomes Gas as it is more volatile. This process takes place in each tray. The entire gaseous nitrogen is piped out from the top of the upper column through the subcoolers and heat exchangers. Similarly Liquid Oxygen at bottom of condenser is carried away.
13. Generally the purity of Oxygen will be 99.5 % and Nitrogen about 96 % to 97.5 % , when the plant is exclusively operated for oxygen. If nitrogen is also required, a part of RL vapor is bled out from the center of upper column. By doing this the waste nitrogen purity will increase to 99.5 % and the Oxygen production will fall.

The plant should be operated in such a manner that it is not too cold or too warm. If the cold box is too cold, the Nitrogen will condense and mix with Liquid Oxygen and the Oxygen purity will fall. If the plant is too warm the oxygen will evaporate with the

nitrogen and reduces the quantity of oxygen. To obtain the optimum result of the plant, check the purity of waste Nitrogen which should not fall below 96%.

4.4 T-s Diagram-

Thermodynamic Temperature-Entropy diagram is very useful to visualize the change in the entropy of the process. Under the ideal condition the area under the T-s diagram gives the heat transferred during the process. The Temperature- Entropy diagram of the above process is shown below. This T-s diagram is shown upto the point where the Air gets liquefied.

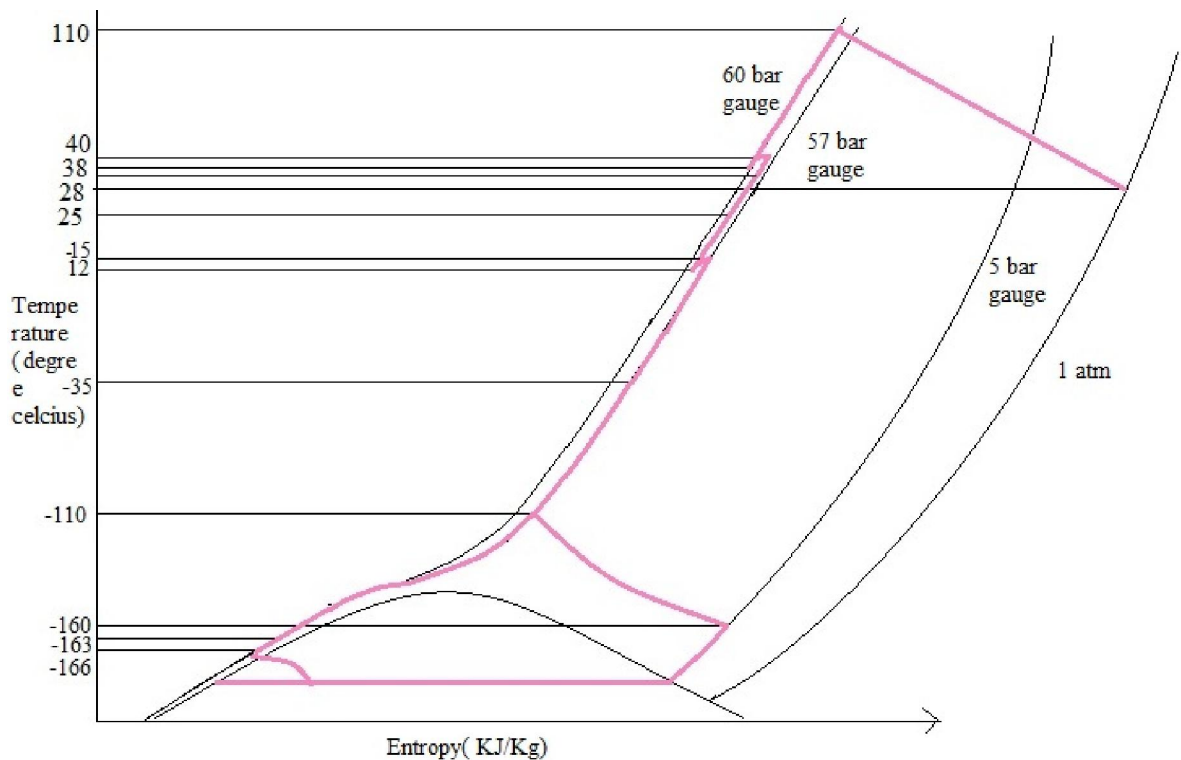


Fig.4.3 : T-s Diagram Air separation process

CHAPTER 5 : MASS, ENERGY AND EXERGY BALANCE OF SYSTEM

A thermodynamic analysis of any system including the energy and exergy analysis provides the opportunity to evaluate the theoretical performance of the system. Thermodynamic analysis is able to define the energy efficiency, exergy efficiency of the system. With the help of this analysis we can find out area of improvement where we can save the energy or can improve our system for better performance. Exergy analysis is based on both the first law and second law of thermodynamics. With the help of exergy analysis we can determine the performance of any system based on exergy which is defined as the maximum amount of work we can obtain if a process is going under reversible condition from its given condition to dead state where it will be in equilibrium with the atmosphere in terms of mechanical and thermal equilibrium. So the exergy will be physical exergy.

5.1 Assumptions-

Following assumptions are used while carrying out the analysis of given system:

1. All the gases are assumed to be real.
2. All the pressure values are given as gauge pressures.
3. Kinetic and Potential energies of the streams are neglected.
4. In the liquid state of air, only nitrogen and oxygen is considered. Mole fractions of other components are assumed to be zero for calculation purpose.

5.2 Reference State -

Since energy and exergy are always measured from some reference state. There is no meaning of measurement of energy and exergy without reference state. In this thesis the reference state of air and water is assumed to be 0°C. For Nitrogen, Oxygen and mixture of Nitrogen-Oxygen also the reference states are assumed to be 0°C. Thermodynamic properties for pure substances are calculated from EES and for the mixture it is calculated from REFPROP.

5.3 Energy of Moist Air-

Energy of moist air (mixture of air and water vapour) per kg of dry air is calculated from EES in the following manner:

$$(h_{ma})_{T,P} = [(h_{dry\ air})_{T,P} - (h_{dry\ air})_{0^\circ C}] + \omega(h_{water})_{T,P_{water}}$$

Where,

h_{ma} = Enthalpy of moist air per Kg of dry air

$h_{dry\ air}$ = Enthalpy of dry air calculated by EES at temp T and partial pressure of air(P_{air})

ω = Specific humidity

h_{water} = Enthalpy of water vapour at temp T and partial pressure P_{water}

5.4 Properties of mixture of Nitrogen- Oxygen-

To calculate the properties of mixture of Nitrogen- Oxygen, a new mixture is defined in Refprop software. The outcomes of Refprop are given below:

1. Saturation table of N₂-O₂ mixture considering 60% moles of nitrogen and 40% moles of Oxygen.

	Liquid Phase Temperature (°C)	Vapor Phase Temperature (°C)	Pressure (bar_g)	Liquid Phase Density (kg/m³)	Vapor Phase Density (kg/m³)	Liquid Phase Enthalpy (kJ/kg)
1	-192.66	-188.73	0.00000	935.38	4.4317	-129.75
2	-191.00	-187.13	0.20000	927.64	5.2347	-126.60
3	-189.54	-185.72	0.40000	920.74	6.0291	-123.81
4	-188.22	-184.45	0.60000	914.47	6.8166	-121.30
5	-187.03	-183.30	0.80000	908.71	7.5986	-119.01
6	-185.92	-182.24	1.00000	903.36	8.3769	-116.89
7	-184.90	-181.26	1.20000	898.35	9.1495	-114.91
8	-183.95	-180.34	1.40000	893.63	9.9169	-113.06
9	-183.05	-179.47	1.60000	889.15	10.6888	-111.32
10	-182.20	-178.66	1.80000	884.88	11.4553	-109.66
11	-181.39	-177.88	2.00000	880.80	12.217	-108.09
12	-180.62	-177.15	2.20000	876.89	12.980	-106.58
13	-179.89	-176.45	2.40000	873.12	13.744	-105.14
14	-179.19	-175.77	2.60000	869.49	14.501	-103.76
15	-178.52	-175.13	2.80000	865.97	15.251	-102.42
16	-177.87	-174.50	3.00000	862.57	16.021	-101.13
17	-177.24	-173.91	3.20000	859.26	16.790	-99.890
18	-176.64	-173.33	3.40000	856.05	17.539	-98.683
19	-176.05	-172.77	3.60000	852.92	18.298	-97.513
20	-175.49	-172.22	3.80000	849.86	19.057	-96.375
21	-174.94	-171.70	4.00000	846.88	19.817	-95.268
22	-174.40	-171.19	4.20000	843.97	20.577	-94.189
23	-173.88	-170.69	4.40000	841.11	21.338	-93.137
24	-173.38	-170.21	4.60000	838.32	22.100	-92.110
25	-172.89	-169.74	4.80000	835.58	22.862	-91.105
26	-172.41	-169.28	5.00000	832.88	23.625	-90.123
27	-171.94	-168.83	5.20000	830.24	24.389	-89.161
28	-171.48	-168.39	5.40000	827.64	25.155	-88.218
29	-171.03	-167.96	5.60000	825.09	25.921	-87.294
30	-170.59	-167.54	5.80000	822.57	26.689	-86.387
31	-170.16	-167.13	6.00000	820.10	27.456	-85.496
32	-169.74	-166.73	6.20000	817.65	28.226	-84.621
33	-169.33	-166.34	6.40000	815.25	29.000	-83.760
34	-168.92	-165.95	6.60000	812.87	29.773	-82.914
35	-168.53	-165.57	6.80000	810.53	30.548	-82.081
36	-168.14	-165.20	7.00000	808.21	31.325	-81.261
37	-167.75	-164.84	7.20000	805.92	32.103	-80.452
38	-167.36	-164.48	7.40000	803.66	32.883	-79.656
39	-167.01	-164.13	7.60000	801.42	33.665	-78.870
40	-166.64	-163.78	7.80000	799.21	34.449	-78.096
41	-166.29	-163.44	8.00000	797.02	35.235	-77.331
42	-165.93	-163.10	8.20000	794.86	36.023	-76.576
43	-165.59	-162.77	8.40000	792.71	36.812	-75.831
44	-165.26	-162.45	8.60000	790.58	37.604	-75.095
45	-164.91	-162.12	8.80000	788.48	38.399	-74.367
46	-164.58	-161.81	9.00000	786.39	39.195	-73.648
47	-164.25	-161.50	9.20000	784.32	39.993	-72.937
48	-163.93	-161.19	9.40000	782.26	40.794	-72.233
49	-163.61	-160.89	9.60000	780.23	41.598	-71.537
50	-163.30	-160.59	9.80000	778.21	42.403	-70.848
51	-162.99	-160.29	10.0000	776.20	43.212	-70.166
52	-162.68	-160.00	10.2000	774.21	44.022	-69.491

Table 5.1 : Saturation Table of Nitrogen/Oxygen mixture

As Clear from the table that the dew point and bubble point temp of mixture at 5 bar gauge pressure is -172.41 °C and -169.28 °C respectively for the given composition. Hence based on

the table above the outlet temperature of liquid mixture of Nitrogen-Oxygen at high pressure column exit is assumed to be (-172.41 °C).

2. Temperature- composition diagram of mixture at 5 bar gauge pressure is given below:

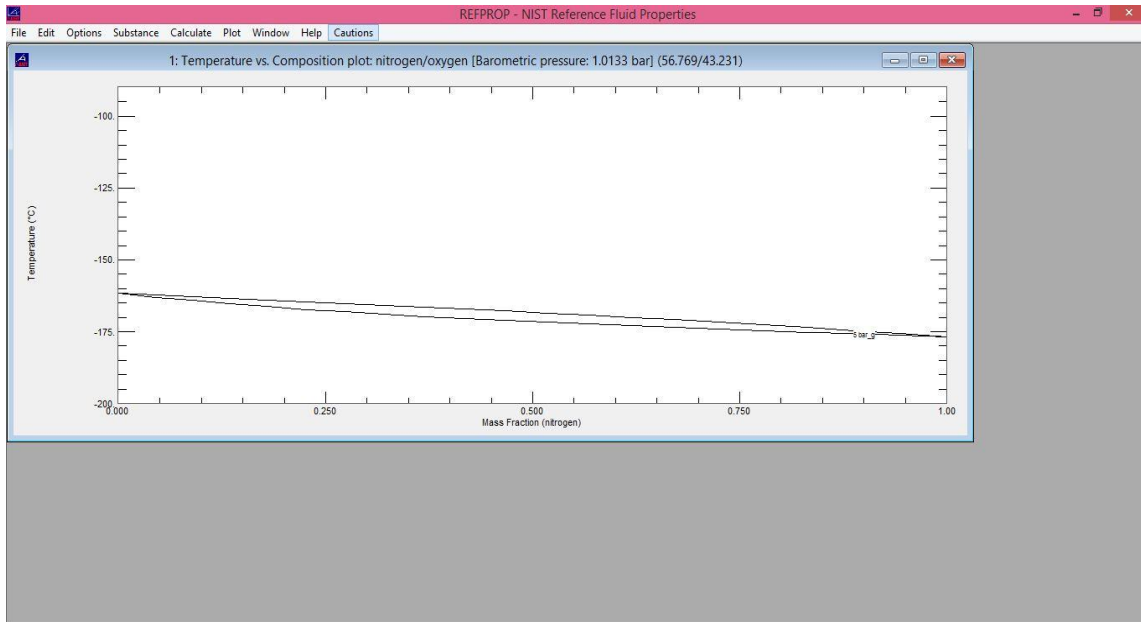


Fig.5.1 : Temperature-Composition diagram of Oxygen/Nitrogen mixture at 5 bar gauge pressure

It is clear from the above figure that mixture of Nitrogen and Oxygen can only be in liquid state if the temperature of mixture is lower than or equal to -172.41 °C.

3. Temperature- Composition diagram of Nitrogen- Oxygen at 0.5 bar gauge pressure is given below :

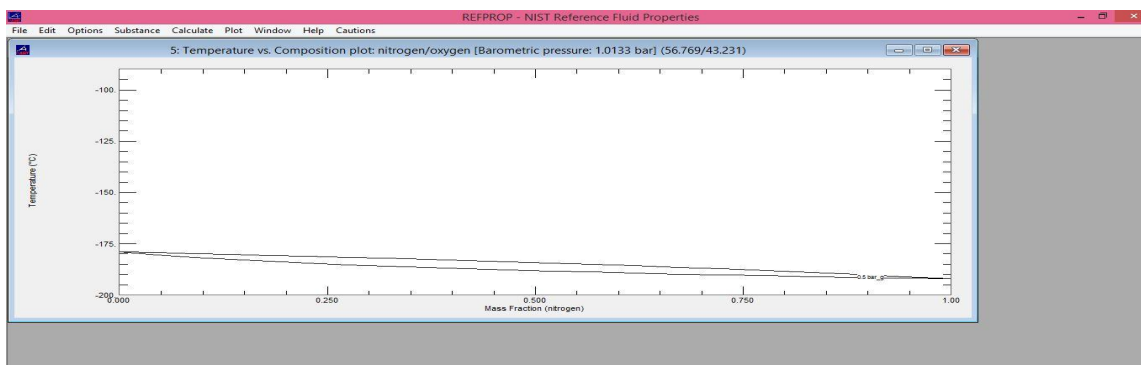


Fig.5.2 : Temperature-Composition diagram of Oxygen/Nitrogen mixture at 0.5 bar gauge pressure

It is clear from the above figure that the temperature of liquid state of pure oxygen will be -178.9 °C. Hence the exit temperature of liquid oxygen at exit low pressure is assumed to be -178.9 °C. The exit temperature of Nitrogen gas is assumed to be -192.2 °C which is saturation temperature of Nitrogen at 0.5 bar gauge pressure as depicted in the above figure.

4. Enthalpy of Rich liquid (60% Nitrogen & 40% Oxygen) at 5 bar gauge pressure is calculated from Refprop and given below:

	Temperature (°C)	Pressure (bar_g)	Density (kg/m ³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)
1	-172.41	5.0000	832.91	-90.132	3.4600
2	-183.00	5.0000	889.95	-111.04	3.2408
3					

Fig.5.3 : Enthalpy of Rich Liquid from Refprop

5. Enthalpy of Poor liquid (97.5% Nitrogen & 2.5% Oxygen) at 5 bar gauge pressure is calculated from Refprop and given below:

	Mass Frac. (nitrogen)	Mass Frac. (oxygen)	Temperature (°C)	Pressure (bar_g)	Density (kg/m ³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)
1	0.97150	0.028500	-184.00	5.0000	759.05	-98.261	3.1528
2	0.97150	0.028500	-191.00	5.0000	793.66	-112.81	2.9829
3							

Fig.5.4 : Enthalpy of Poor Liquid from Refprop

5.5 Mass Balance in Separating Column-

Mass flow rate of liquid oxygen = 0.14 kg/sec

Applying the mass balance in air separating unit :

$$(\dot{m}_{in}) - (\dot{m}_{out}) = \left(\frac{dm}{dt}\right) \dots\dots\dots(1)$$

In case of steady flow the right hand term will be zero because no changes will be there with respect to time after the steady state has been reached. Hence from eq (1)

$$(\dot{m}_{in}) - (\dot{m}_{out}) = 0$$

$$(\dot{m}_{RL,in}) + (\dot{m}_{PL,in}) + (\dot{m}_{air,in}) + (\dot{m}_{RL,out}) - (\dot{m}_{PL,out}) - (\dot{m}_{oxy}) - (\dot{m}_{N2}) = 0$$

Since $(\dot{m}_{RL,in}) = (\dot{m}_{RL,out})$

$$(\dot{m}_{PL,in}) = (\dot{m}_{PL,out})$$

Hence $(\dot{m}_{air,in}) = (\dot{m}_{oxy}) + (\dot{m}_{N2})$

$$0.6432 = 0.14 + (\dot{m}_{N2})$$

$$\dot{m}_{N2} = 0.5032 \text{ kg/sec}$$

5.6 Calculation for mass of water vapour condensed in system –

Water vapour is condensed and separated out in moist separator in system wherever the moist air is cooled below the dew point of water vapour present in the mixture. The amount of water vapour condensed at different stages can be calculated as :

5.6.1 Compressor-

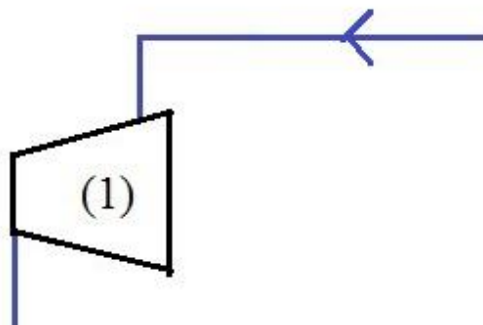


Fig.5.5 : Compressor

Inlet- P=1 atm absolute

$$T= 28^{\circ}\text{C}$$

$$\phi= 0.70$$

Exit- P=60 bar gauge

$$T= 110^{\circ}\text{C}$$

$$\dot{V} = 1800 \text{ m}^3/\text{hr}$$

Free air delivered = 1800 m³/hr

$$= 1800/3600=0.5 \text{ m}^3/\text{hr}$$

Density of free air= 1.29 kg/m³

Hence mass of moist air= density*volume

$$= 0.5*1.29$$

$$= 0.6450 \text{ kg/sec}$$

Since moist air is a mixture of dry air and water vapour hence

$$\dot{m}_a + \dot{m}_w = 0.6450 \dots \dots \dots (2)$$

Where \dot{m}_a = mass of dry air

\dot{m}_w = mass of water vapour

At exit of compressor

$$\phi=0.15$$

$$\phi=P_v/P_{vs}$$

$$= P_v/1.432$$

$$P_v= 0.2148 \text{ bar}$$

$$\omega_{\text{exit}}= 0.622*P_v/(P-P_{vs})$$

$$= 0.622*0.2148/(61.01325-0.2148)$$

$$= 0.002197$$

Since $\omega = \frac{\text{mass of water vapor}}{\text{mass of dry air}}$

$$\omega_{\text{exit}} = (\dot{m}_w)_{\text{exit}} / \dot{m}_a = 0.002197$$

$$(\dot{m}_w)_{\text{exit}} = 0.002197 \dot{m}_a \quad \dots\dots\dots(3)$$

Solving eq (2) & (3)

$$\dot{m}_a = 0.6436 \text{ kg/sec}$$

$$(\dot{m}_w)_{\text{exit}} = 0.0014 \text{ kg/sec}$$

At inlet-

$$\phi = 0.70$$

$$\phi = P_v / P_{vs}$$

$$= P_v / 0.03782$$

$$P_v = 0.026474 \text{ bar}$$

$$\omega_{\text{in}} = 0.622 * P_v / (P - P_{vs})$$

$$= 0.622 * 0.03782 / (1.013250 - 0.026474)$$

$$= 0.016687$$

$$\omega_{\text{in}} = (\dot{m}_w)_{\text{in}} / \dot{m}_a = 0.002197$$

hence $(\dot{m}_w)_{\text{in}} = 0.01074 \text{ kg/sec}$

mass of water vapour condensed in compressor = $0.01074 - 0.0014$

$$= 0.00934 \text{ kg/sec}$$

$$= 33.624 \text{ kg/hr}$$

5.6.2 After Cooler-

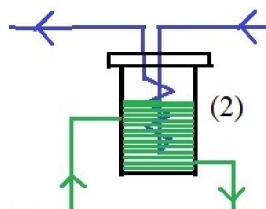


Fig.5.6 : After-cooler

At inlet-

P=60 bar gauge

T=110°C

$\phi=0.15$

$\omega_{in}=0.002197$

At exit-

P=60 bar gauge

T= 38°C

$\phi = 1$

$\dot{m}_a = 0.6436 \text{ kg/sec}$

Since $\phi=(P_v)_{exit}/P_{vs}$

$1 = (P_v)_{exit}/0.0663$

$(P_v)_{exit} = 0.0663 \text{ bar}$

$$\begin{aligned}\omega_{exit} &= 0.622 (P_v)_{exit}/(P-(P_v)_{exit}) \\ &= 0.622*0.0663/(61.01325-0.0663) \\ &= 0.0006766\end{aligned}$$

$$\omega_{exit} = (\dot{m}_w)_{exit}/\dot{m}_a = 0.0006766$$

$$(\dot{m}_w)_{exit} = 0.0004354$$

Mass of water vapour condensed in after cooler = 0.0014-0.0004354

$$= 0.0009646 \text{ kg/sec}$$

$$= 3.4725 \text{ kg/hr}$$

5.6.3 Cascade Cooler-

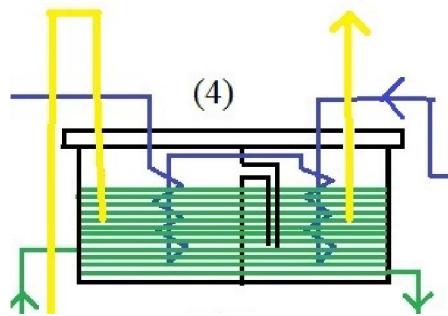


Fig.5.7 : Cascade Cooler

Inlet-

P= 59 bar gauge

T= 40°C

Since pressure drop occurs and temperature also increases after moist separator, relative humidity at inlet of cascade cooler will get changed i.e. the air will not be in saturated condition at inlet of cascade cooler.

Since ω will be constant between moist separator and cascade cooler . Hence,

$$\omega = 0.0006766 = 0.622 * (P_v)_{in} / (P - (P_v)_{in})$$

$$(P_v)_{in} = 0.06521 \text{ bar}$$

$$\phi_{in} = (P_v)_{in} / P_{vs}$$

$$= 0.06521 / 0.07381$$

$$= 0.8834$$

At the inlet of cascade cooler partial pressure is 0.06521 bar. At this pressure the saturation temperature is 37.69°C which is greater than 25°C (cascade cooler exit temperature). Hence at the exit $\phi=1$.

At Exit-

P= 58.5 bar

$\phi=1$

T= 25°C

$$\phi = P_v / P_{vs}$$

$$1 = P_v / 0.03169$$

$$P_v = 0.03169 \text{ bar}$$

$$\begin{aligned} \omega_{\text{exit}} &= 0.622 (P_v)_{\text{exit}} / (P - (P_v)_{\text{exit}}) \\ &= 0.622 * 0.03169 / (59.51325 - 0.03169) \\ &= 0.00033138 \end{aligned}$$

$$\omega_{\text{exit}} = (\dot{m}_w)_{\text{exit}} / \dot{m}_a = 0.00033138$$

$$(\dot{m}_w)_{\text{exit}} = 0.000213278 \text{ kg/sec}$$

$$\begin{aligned} \text{Mass of water vapour condensed in cascade cooler} &= 0.0004354 - 0.000213278 \\ &= 0.00022212 \text{ kg/sec} \\ &= 0.7996 \text{ kg/hr} \end{aligned}$$

5.6.4 Chilling Unit –

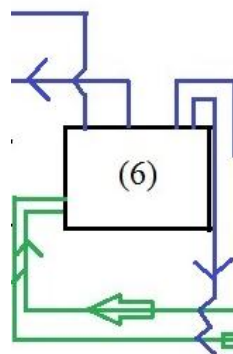


Fig.5.8 : Chilling Unit

Inlet-

$$P = 58 \text{ bar gauge}$$

$$T = 26^\circ\text{C}$$

ϕ = to be calculated since temperature changed

$$\omega_{\text{in}} = 0.00033138$$

since ω is constant hence

$$\omega_{in} = 0.00033138 = 0.622 * P_v / (59.51325 - P_v)$$

$$P_v = 0.03169 \text{ bar}$$

$$P_{vs} = 0.03363 \text{ bar}$$

$$\phi_{in} = 0.03169 / 0.03363$$

$$= 0.9423$$

At Exit-

$$P = 58 \text{ bar gauge}$$

$$T = 12^\circ\text{C}$$

$$\phi = 1 = (P_v)_{exit} / P_{vs}$$

$$1 = (P_v)_{exit} / 0.01403$$

$$(P_v)_{exit} = 0.01403 \text{ bar}$$

$$\omega_{exit} = 0.622 (P_v)_{exit} / (P - (P_v)_{exit})$$

$$= 0.622 * 0.01403 / (59.01325 - 0.01403)$$

$$= 0.0001479$$

$$\omega_{exit} = (\dot{m}_w)_{exit} / \dot{m}_a = 0.0001479$$

$$(\dot{m}_w)_{exit} = 0.000095195 \text{ kg/sec}$$

$$\text{Mass of water vapour condensed in cascade cooler} = 0.000213278 - 0.000095195$$

$$= 0.000118083 \text{ kg/sec}$$

$$= 0.4250 \text{ kg/hr}$$

5.6.5 Alumina filter & Mollier Sieve battery-

Alumina filter is used to remove water from the air. Mollier sieve is used to remove CO₂ and other hydrocarbons from the air. At the exit of Mollier Sieve the air will be free from any CO₂ and water traces.

$$\text{Mass of water removed} = 0.000095195 \text{ kg/sec}$$

$$= 0.3427 \text{ kg/hr}$$

5.7 Energy Analysis and Energetic Evaluation Parameters-

By the first law of Thermodynamics the energy analysis of a control volume can be described as follows:

$$\dot{Q} + \dot{W} = \sum \dot{E}_{out} - \sum \dot{E}_{in}$$

Neglecting the magnetic, electrical, nuclear and surface tension, the energy balance can be expressed as:

$$\dot{Q} + \dot{W} = \dot{m}(\dot{h}_{out} - \dot{h}_{in})$$

Where \dot{h} = Enthalpy of the given stream with respect to reference state.

Energy Efficiency (η) is defined as rate of energy out to the rate of Energy in. Efficiency of Heat Exchanger is defined as:

$$\eta_{HE} = \frac{\dot{E}_{cold,o} - \dot{E}_{cold,i}}{\dot{E}_{hot,i} - \dot{E}_{cod,o}}$$

Efficiency of compressor is defined as:

$$\eta_{comp} = \frac{\dot{E}_{out} - \dot{E}_{in}}{\dot{W}_{comp}}$$

Efficiency of other component of air separation unit is defined as :

$$\eta_j = \frac{\dot{E}_{o,j}}{\dot{E}_{i,j}}$$

Energetic improvement potential (EIP) is defined as:

$$EIP_k = (1 - \eta)E_{L,k}$$

Where $E_{L,k}$ is the energy loss in the k^{th} component.

Relative Energy Loss (β) of the considered component is defined as:

$$\beta_k = \frac{\dot{E}_{L,k}}{\dot{E}_{TL}}$$

Where \dot{E}_{TL} is the total energy loss of the given system.

5.8 Exergy Analysis and Exergetic Evaluation Parameters-

Exergy analysis of any control volume can be defined as:

$$\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k + \dot{E}x_w + \sum \dot{E}x_o - \sum \dot{E}x_i = \dot{E}x_D$$

Where \dot{Q}_k is the rate of heat transfer

$\dot{E}x_w$ = Rate of exergy transfer due to work

$\dot{E}x_o$ = Rate of Output Exergy

$\dot{E}x_i$ = Rate of input Exergy

$\dot{E}x_D$ = Exergy Destruction Rate

T_0 = Ambient Environment Temperature

T_k = Heat source Temperature

Since the magnetic, electrical, nuclear and surface tension interactions are not there, hence exergy can be expressed as:

$$\dot{E}x = \dot{m}(h - h_0) - T_0(s - s_0)$$

Where h is the enthalpy per unit mass and s is the entropy per unit mass of given stream.

Exergy Efficiency (ψ) is defined as rate of output exergy to rate of input exergy. Exergy efficiency of a heat exchanger is given by:

$$\psi_{HE} = \frac{\dot{E}x_{cold,o} - \dot{E}x_{cold,i}}{\dot{E}x_{hot,i} - \dot{E}x_{cold,o}}$$

Exergy efficiency of compressor is given by :

$$\psi_{comp} = \frac{\dot{E}x_o - \dot{E}x_i}{\dot{W}_{comp}}$$

In air separation system exergy efficiency of any system can be defined as :

$$\psi_j = \frac{\dot{E}x_{o,j}}{\dot{E}x_{i,j}}$$

The Exergetic Improvement Potential (ExIP) is defined as :

$$ExIP = (1 - \psi) \dot{E}x_{D,k}$$

$\dot{E}x_{D,k}$ is the rate of exergy destruction in a given component.

Relative Exergy Loss is defined as :

$$\alpha_k = \frac{\dot{E}x_{D,k}}{\dot{E}x_{TD}}$$

Where $\dot{E}x_{TD}$ is the rate of total exergy destruction in the system.

Entropy Generation (σ) in any component is defined as :

$$\sigma_k = \frac{\dot{E}x_{D,k}}{T_0}$$

CHAPTER 6 : RESULT AND DISCUSSION

The Plant is analyzed with respect to First law and Second law analysis of thermodynamics. The main parameters involved are the energy efficiency, exergy efficiency, energy loss, exergy loss, energy and exergy improvement parameters, exergy destruction and entropy generation. Energy loss in the system shows the loss of heat or work to the surrounding. Where as the exergy loss in the system shows the opportunity of work we can obtain from the system or in another word it shows the work dissipation due to the irreversibility in the system. Entropy generation is the measurement of irreversibility in the system. Higher the entropy generation higher will be the irreversibility in the system. For the reversible processes the entropy generation is zero. Entropy generation negatively affects the system and decreases its efficiency. Energy efficiency of a component shows how usefully the energy is utilized where as the exergy efficiency of the system shows how the system close to the reversible one. In the present study another parameters are also investigated such as relative energy loss and relative exergy loss. Relative Energy Loss represent the percentage loss of energy in a given component with reference to the total loss of energy in the given system. In the same manner Relative Exergy Loss represents the percentage exergy loss in the given component with respect to the total exergy loss in the system.

Sr. No.	Component	Energy In (KW)	Energy Out (KW)	Energy Loss (KW)	Efficiency (%) / COP	Relative Energy Loss (β)	EIP
1	Compressor	395.36	70.796	324.564	0.179	0.763745	266.47
2	After Cooler	193.5	193.5	0	1	0	0
3	Chilling Unit	37.09	-2.43	39.52	1.63	0.092996	-
4	Mol. Sieve	12.89	12.89	0	1	0	0
5	Expansion Engine	-58.94	-65.58	6.64	0.89	0.015625	0.73
6	Air Separating Unit	-339.39	-346.46	7.07	0.97	0.016637	0.21
		Hot Fluid	Cold Fluid				
		Energy In	Energy In	Energy Out	Energy In	Energy Out	
7	Cascade Cooler	19.57	8.42	7.82	12.58	6.39	0.015037
8	Heat Exchanger 1	1.106	-35.84	-23.65	6.25	7.05	0.01659
9	Heat Exchanger 2	-34.8	-98.24	-73.82	-23.69	13.31	0.03132
10	Liquifier	-39.3	-75.6	-91.05	-73.82	19.07	0.044874
	Rich Liquid						
11	Subcooler	-113.99	-121.3	-97.13	-91.05	1.23	0.002897
	Poor Liquid						
12	Subcooler	-81.01	-84.14	-102.4	-99.39	0.12	0.000282
	Oxygen Liquid						
13	Subcooler	-58.94	-60.12	-99.39	-97.13	-3.07	-

Table 6.1 : Parameters related to Energy interaction of individual component

Sr. No.	Component	Exergy In (KW)	Exergy Out (KW)	Exergy Loss (KW)	Exergy Efficiency ψ (ψ)	Relative Exergy Loss (α)	Entropy Generation (σ)	Exergy Improvement potential (ExIP)
1	Compressor	350.62	235.72	114.9	0.672	0.357	0.386	37.687
2	After Cooler	235.78	228.93	6.85	0.97	0.0212	0.023	0.2055
3	Cascade Cooler	239.52	226.89	12.63	0.947	0.0392	0.042	0.669
4	Chilling Unit	465.09	449.71	15.38	0.97	0.0477	0.052	0.461
5	Mol. Sieve	230.56	223.8	6.76	0.97	0.021	0.023	0.203
6	Heat Exchanger 1	242.88	239.72	3.16	0.986	0.009	0.011	0.044
7	Heat Exchanger 2	285.27	282.46	2.81	0.99	0.008	0.009	0.028
8	Liquifier	208.37	190.07	18.3	0.912	0.0568	0.061	1.61
9	Expansion Engine	155.6	103.5	52.1	0.708	0.162	0.175	15.213
10	Air Separating Col.	622.63	544.28	78.35	0.874	0.243	0.263	9.872
11	Rich Liquid Subcooler	296.41	292.56	3.85	0.987	0.012	0.013	0.05
12	Poor Liquid Subcooler	259.44	258.14	1.3	0.995	0.004	0.004	0.007
13	Oxygen Liquid Subcooler	191.94	186.31	5.63	0.97	0.0175	0.019	0.169

Table 6.2 : Parameters related to Exergy interaction of individual component

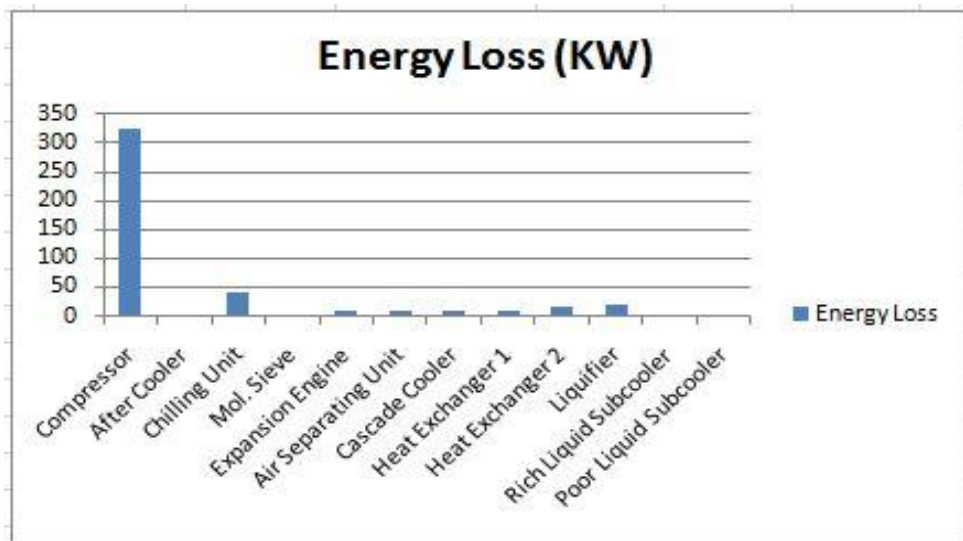


Fig.6.1 : Energy Loss in individual component

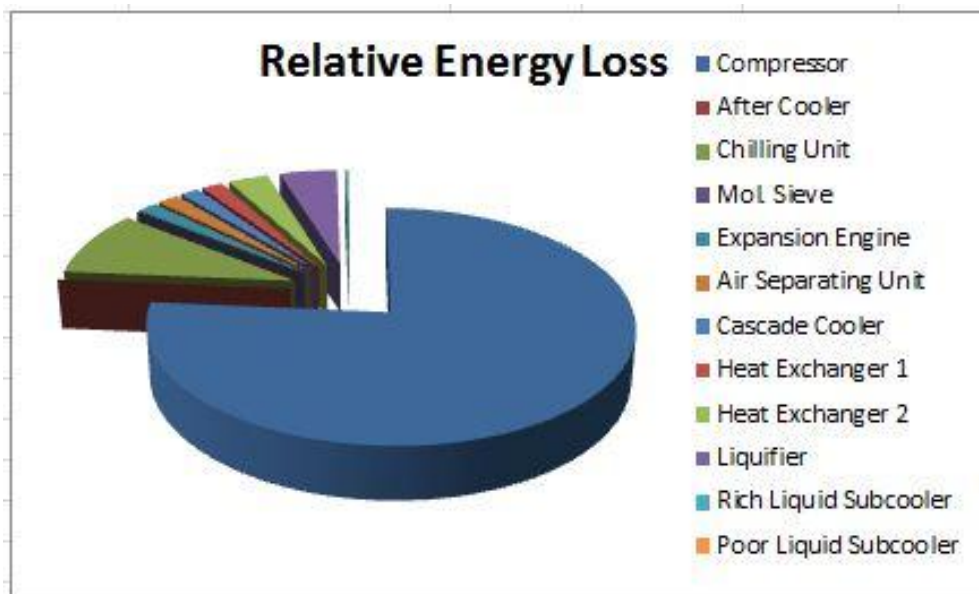


Fig.6.2 : Relative Energy Loss in individual component

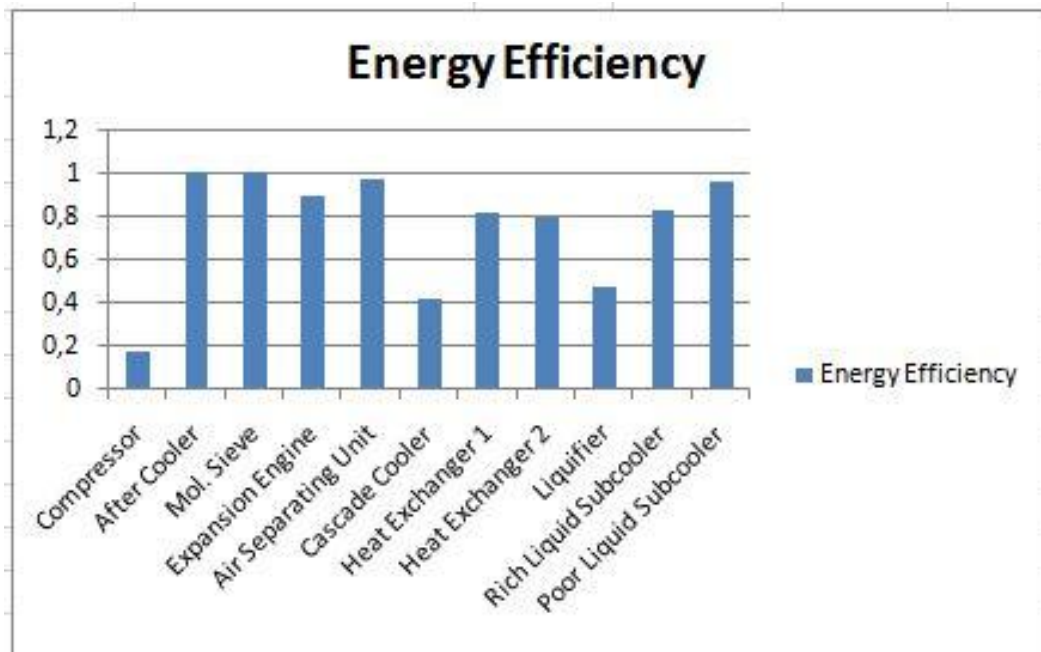


Fig.6.3 : Energy Efficiency of individual component

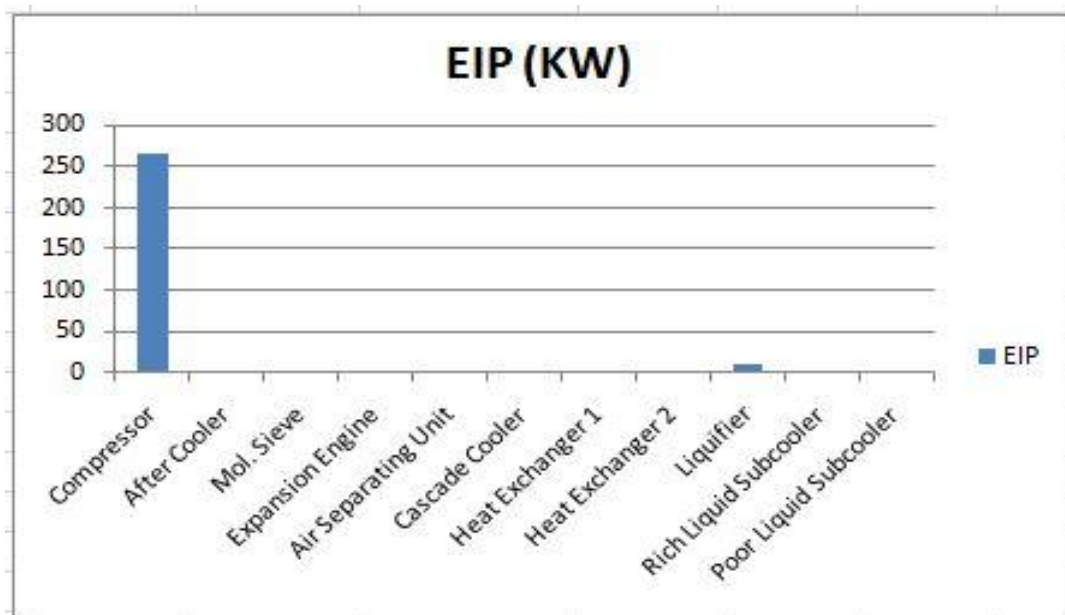


Fig.6.4 : Energy Improvement Performance of individual component

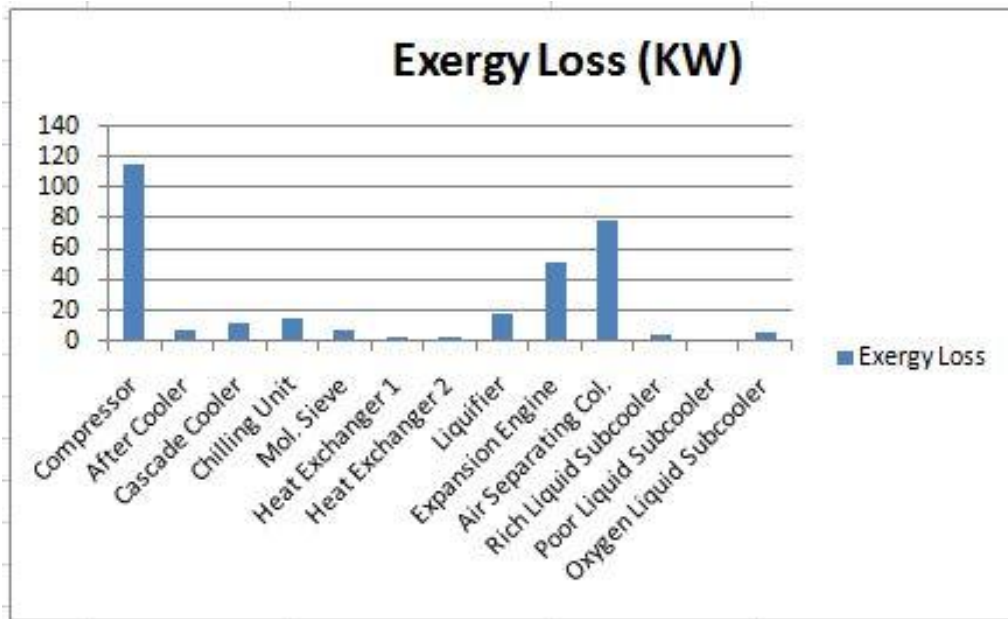


Fig.6.5 : Exergy Loss in individual component

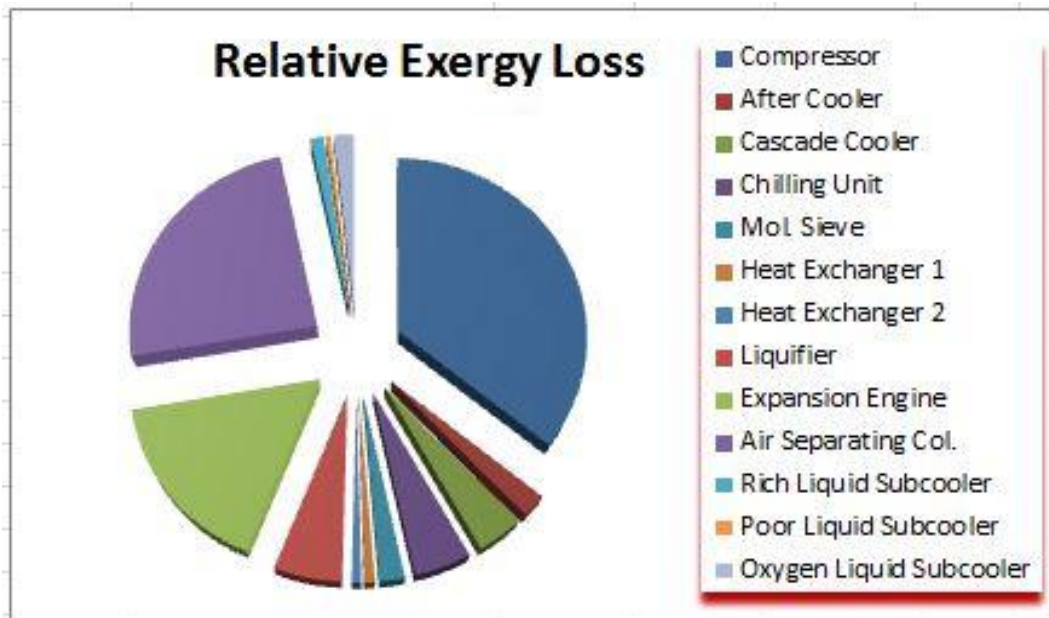


Fig.6.6 : Relative Exergy Loss in individual component

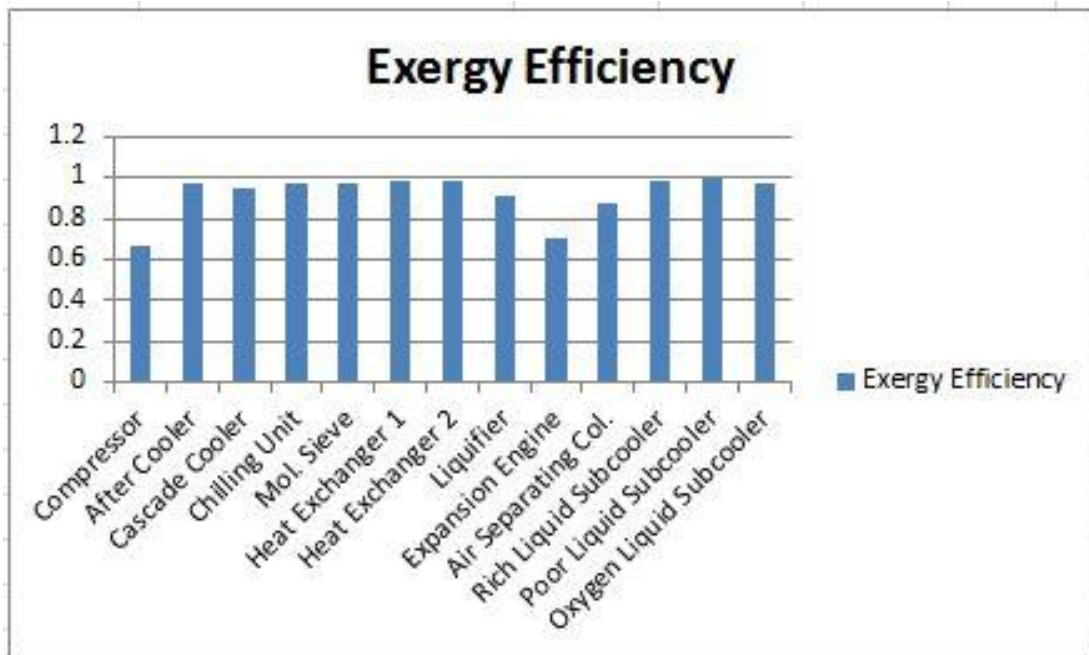


Fig.6.7 : Exergy Efficiency of individual component

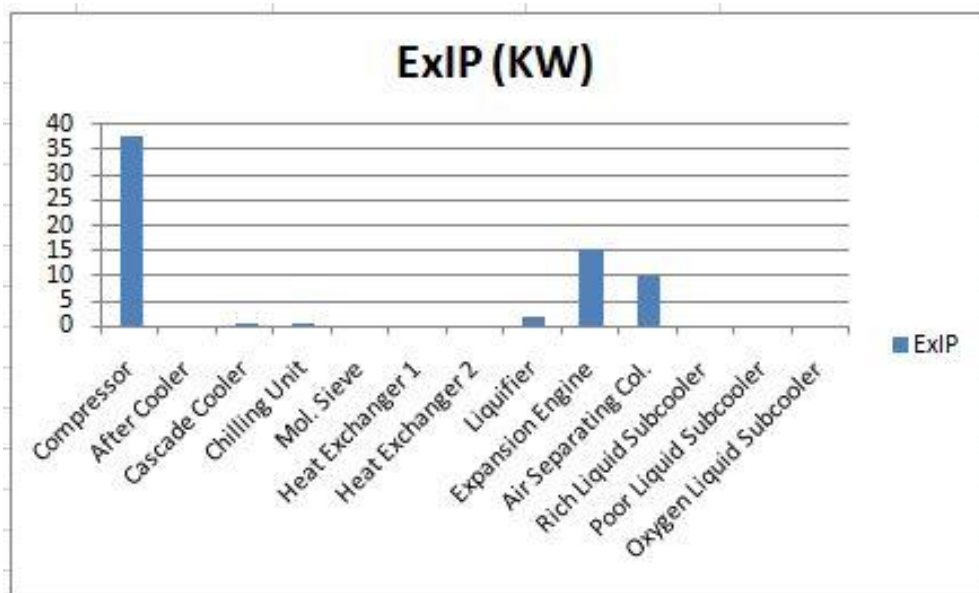


Fig.6.8 : Exergy Improvement Performance of individual component

6.1 Energy Analysis Results:

Some important results in terms of energy analysis are as follows:

1. Highest Energy efficiency is 97 % which is of Air Separation unit while the lowest energy efficiency is 17.9 % which is of compressor. Compressor efficiency is low because most of the energy is lost to the surrounding.
2. Lowest Relative Energy loss is zero which is in after-cooler and molecular sieve. The highest relative energy loss is 76.37 % which is in the compressor. The reason is most of the energy in compressor is lost to the surroundings.
3. The highest Energy Improvement Potential is 266.47 KW which is related to compressor while the lowest Energy Improvement Potential is 0 KW related to Molecular Sieve and After cooler.
4. Energetic Efficiency of only three components are less than 0.5.
5. Energy loss in compressor is 324.564 KW, while the summation of Energy loss in the rest of the component is 100.4 KW.
6. Relative loss of 11 component out of 13 components is less than 0.1, whereas relative loss of only compressor is 0.7637.
7. Energetic Improvement Potential of 11 out of 13 components are very low.

6.2 Exergy Analysis Results:

Some important results in terms of energy analysis are as follows:

1. Highest Exergy Efficiency is 99.5 % which is of Poor Liquid Subcooler while the lowest Exergy Efficiency is 67.2 % which is of Compressor.
2. Highest Relative Exergy Loss is 0.357 which is in the compressor while the lowest Relative Exergy Loss is 0.004 which is in Poor Liquid Subcooler.
3. Highest Exergy Improvement Potential is 37.687 KW which is in Compressor, while the Lowest Exergy Improvement Potential is 0.007 KW which is in Poor Liquid Subcooler.
4. Exergy Efficiency of each component is greater than 0.5. Only two components out of 13 components have the exergy efficiency below 0.8.
5. Exergy destruction in 10 components out of 13 components is 76.67 KW, while the Exergy destruction in Compressor, Expansion Engine and Air Separating Column is 245.35 KW.
6. Relative Exergy Loss of only three components out of 13 components is greater than 0.1.
7. Exergetic Improvement Potential of 10 components out of 13 components are very low.

6.3 Amount of Water separated out in different stages-

Sr.No.	Components	Amount of water separated	Unit
1	Compressor	33.624	Kg/hr
2	After Cooler	3.4725	Kg/hr
3	Cascade Cooler	0.7996	Kg/hr
4	Chilling Unit	0.425	Kg/hr
5	Molecular Sieve	0.3427	Kg/hr

Table 6.3 : Amount of water vapour separated in different stages

As shown in the above table maximum amount of water vapour is condensed in the compressor itself.

CHAPTER 7 : CONCLUSION

A case study is performed for an air separation process. Energy and Exergy analysis are performed to evaluate its parameters and to find out its performance. Energy and exergy methods are employed which enable us to develop a systematic approach that can be used to identify the sites of the real destructions/losses of valuable energy in process. The effect of several design parameters were observed on energy and exergy analysis of the process. The conclusions of the present analysis can be summarized as follows:

- The lowest energy efficiency component is the compressor, which have only 17.9 % efficiency. There are lots of opportunity to increase its efficiency and to use its heat.
- The highest energy improvement potential is 266.47 KW, which is also for compressor.
- Compressor exergy efficiency is also low, which is 67.2 %. This figure shows that there is a large scope to improve its performance.
- Maximum exergy destruction has been taken place Compressor , Expansion Engine and Air Separating Column. The total exergy destruction in these three components is 245.35 KW, while the total exergy destruction is 322.02 KW. It is clear from this result that these three components have highest irreversibility in the system which can be improved.

From the above results shown, it is possible to find out the component, which needs the development to make the system more effective and more efficient. Energy and Exergy related parameters in the given system have good values. In addition, except the few components Energetic Improvement Potential and Exergetic Improvement Potential of the components are very low. Besides the results shown it is not possible to make larger changes in the Air Separation System. More insulation can be add to minimize the energy loss. Some components can be changed with the more reliable and more efficient components. Another option is to design the Air Separation plant keeping in mind the above results and by simulating it on software such as Aspen Plus to optimize the results.

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