Design and Thermal Analysis of Rectification Column for Separation of Nitrogen and Oxygen using Rectification Column Method

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Abstract

In the current world scenario, the main emphasis is laid on the judicial use of energy, which is also the one word definition of energy conservation. This can be done by research on the energy consuming devices in various fields. In cryogenic engineering, one of the most important machine is a rectification column, and it consumes high amount of energy, hence its heat loss analysis must be done, in order to get exact amount of heat leakage at various stages. The air separation process requires a very tight integration of heat exchangers and separation columns to obtain a good efficiency and all the energy for refrigeration is to be utilized at its best to get maximum possible efficiency. When the main thermal losses in the system are known by the CFD analysis use to analyze the heat losses, and if the heat losses at various stages and points are known they can be minimized by using suitable insulations and the cost can also be minimized.
Keywords: Air separation, rectification column, CFD analysis, insulations, Cryogenic

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I. Introduction

Cryogenic distillation is used to produce large quantities of purified nitrogen, oxygen and argon for the steel, chemical, food processing, semiconductor and health care industries. Cryogenic engineering is a sub stream of mechanical engineering dealing with cryogenics, and related very low temperature processes such as air liquefaction, cryogenic engines (for rocket propulsion), cryosurgery. Generally, temperatures below the boiling point of Nitrogen (77 K) comes under the purview of cryogenic engineering. Cryogenics may be considered as the recent advancement in the field of refrigeration. Though there is no fixed demarcation as to where refrigeration ends and cryogenics begins even then for general reference temperature below –150C are considered as cryogenic temperature. The four gases which mainly contribute for cryogenic application and research are (O2-B.P.90K), (N2-B.P.77K), (Helium-B.P.4.2k) & (H2-B.P.20K). The word "cryogenics" is derived from two Latin words. Cryo - means cold and Genics - means science. Cryogenics is “the science of cold".

Liquefaction is used for analyzing the fundamental properties of gas molecules (intermolecular forces), for storage of gases, for example: LPG, and in refrigeration and air conditioning. There the gas is liquefied in the condenser, where the heat of vaporization is released, and evaporated in the evaporator, where the heat of vaporization is absorbed. Ammonia was the first such refrigerant, and is still in widespread use in industrial refrigeration, but it has largely been replaced by compounds derived from petroleum and halogens in residential and commercial applications. An air separation plant separates atmospheric air into its primary components, typically nitrogen and oxygen, and sometimes also argon and other rare inert gases. Air separation plants are constructed in different forms depending on what products are produced, production capacity, and purity. Then the most appropriate process which has the lowest energy consumption and purchase price is selected. The cryogenic separation process requires a very tight integration of heat exchangers and separation columns to obtain a good efficiency and all the energy for refrigeration is provided by the compression of the air at the inlet of the unit. In addition to the cryogenic distillation method there are other methods such as Membrane, Pressure Swing Adsorption (PSA) and Vacuum Pressure Swing Adsorption (VPSA), which are typically used to separate a single component from ordinary air.

A. *Membrane Separation*

Membrane separation isolates nitrogen from atmospheric air by selective permeation across a membrane wall. The membrane used in this method consists of a bundle of selectively permeable hollow fibers. These fibers allow the “fast” gases (oxygen, carbon dioxide and water vapor) to permeate the membrane wall much faster than the “slow” gas (nitrogen). The membrane separates the original gas mixture into two streams. One stream, called the permeate, contains oxygen, carbon dioxide and water vapor. The other stream, called the product, consists of high-pressure nitrogen. The permeate is vented to the atmosphere and the product, nitrogen, exits the downstream end of the membrane for delivery to the end-user or to a booster if further compression is required.

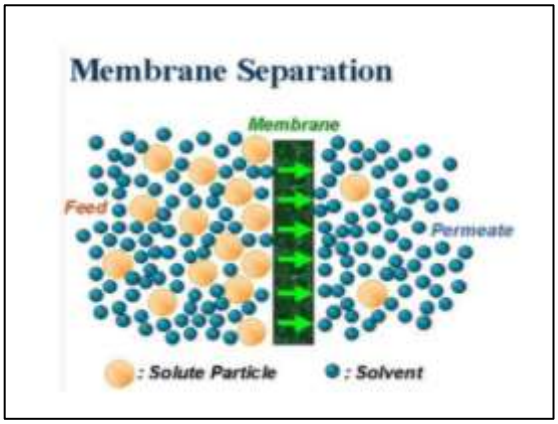


Fig. 1: membrane separation

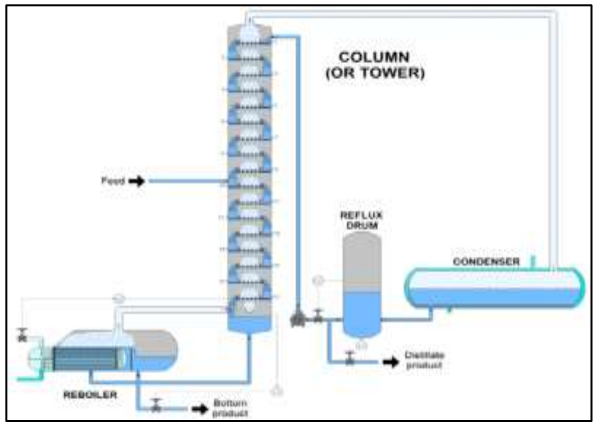


Fig. 2: separation system layout with column.

The purity of the product can be adjusted by changing the operation conditions. If the nitrogen flow rate is decreased, nitrogen purity increases and conversely, by increasing nitrogen flow, nitrogen purity is decreased. A flow/purity control valve at the discharge end of the nitrogen stream, downstream of the flow meter and nitrogen analyzer, allows finite control of flow and therefore purity

B. *Cryogenic Distillation*

Production of high purity oxygen, nitrogen, and argon as used for Semiconductor device fabrication requires cryogenic distillation. Similarly, the only viable sources of the rare gases neon, krypton, and xenon are the distillation of air using at least two distillation columns. Cryogenic ASU's are built to provide nitrogen and/or oxygen and often coproduce argon where liquid products (Liquid nitrogen "LIN", Liquid oxygen "LOX", and Liquid argon "LAR") and gases product (Gaseous oxygen “GOX” and Gaseous nitrogen “GAN”) can only be produced if sufficient refrigeration is provided for in the design.

1) Air compressor with filter. Dust free air is compressed tp a pressure sufficient to get it through the equipment.
2) Air purifying. Mole sieves are used to remove water vapor, carbon dioxide and certain other contaminants.
3) Cooling down the air. In a heat exchanger the air is cooled down close to the dew point by the cold separated gases, which come from the distillation column. If a suitably large enough heat exchanger is used the cold gases can be warmed to a temperature just under that of the incoming air, so that the cold losses become acceptable.
4) Cold production. Production of liquid products requires cold and cold losses occur through the equipment insulation and in the heat exchanger. this cold is produced in a recycle because the gas which does not condense is warmed up and is fed back to the compressor again.
5) Cooling with cooling water. Compressors and other machines need large amounts of cooling water. A large part of the heat removal is in fact cold production.
6) Air separation. The liquid is separated into oxygen, argon, and nitrogen in the distillation columns. The cold gases are fed through the heat exchanger and are warmed-up while the liquids are fed into tank.
7) Coldbox. The cold equipments demand much insulation order to get an acceptable cold loss. So columns, heat exchangers and parts of the cold production equipment are built in a large tower like box, the so-called coldbox

To achieve the low distillation temperatures an Air Separation Unit (ASU) requires a refrigeration cycle that operates by means of the Joule–Thomson effect, and the cold equipment has to be kept within an insulated enclosure (commonly called a "cold box").

The cooling of the gases requires a large amount of energy to make this refrigeration cycle work and is delivered by an air compressor. The process consists of the following main steps.

The designing of recification column consist of several steps. The starting is done by the input conditions required and the detailed study of properties of the various cryogenic gases and fluids involved in the process of distillation.

C. *Parameters to be obtained from Designing*

- Number of plates in column
- plates above the feed(n)
- plates below the feed(m)
- Height of column
- Diameter of column
- Material used for manufacturing of the rectification column
- Mole flow rate of top(D), bottom(B) and inlet feed stream(F)
- Size of condenser and boiler
- Operating pressure

II. MATH

A. *Inlet Conditions and Available Inputs*

1) *Inlet Air Stream (In Liquid Form):*
   - TEMPERATURE : 91K
   - PRESSURE 510 kpa
   - FEED RATE : 48.94 mol s^{-1}
2) *Stream Condition after Passing through Reboiler*
   - TEMPERATURE : 86K
   - PRESSURE 507 kpa
   - FEED RATE : 48.94 mol s^{-1}
3) *Stream after Passing through Joule Thomson Expansion Valve*
   - TEMPERATURE : 80.50K
   - PRESSURE 102 kpa
   - FEED RATE : 48.94 mol s^{-1}
4) *Heat to Be Extracted From Condenser (Q_c)*
   - 812kW
5) *Heat to Be Supplied At Boiler (Q_b)*
   - 753.49kW
6) *Finding feed for the required oxygen liquid stream*
   - FEED FOR OXYGEN REQUIRED(B) = 10 MOL PER SECONDS
   - $F=B+DX_F.F=x_B.B+x_D.D$
   - F=48.94 mol/seconds
   - D=38.94mol/seconds

B. *Finding feed for the required oxygen liquid stream*

1) *GIVEN :*

FEED FOR OXYGEN REQUIRED (B) = 10 MOL PER SECONDS
$X_F= 0.79$
$X_B=0.05$
$X_D=0.98$
F=B+D
$X_F.F=x_B.B+x_D.D$
F=48.94 mol/seconds
D=38.94mol/seconds

C. *Finding heat to be added at bottom of section by inlet stream of air.*

1) *GIVEN:*

Heat to be removed at condenser at constant rate (Q_B) = 800 kW
Enhapies of saturated liquid ($h=h_B=h_D$), and saturated vapours(H) of inlet feed stream are
h=1050 J/mol
H=6916J/mol
$Q_B + h_F.F = Q_D + h_D.D + h_B.B$

Hence we found by the above equations that, heat which should be added at the bottom section in order to achieve the desired boiling rate is equal to (Q_D)= 753 kW.

D. *Finding amount of vapour content in the outlet stream from top.*

$$\frac{D}{v_n} = \frac{H_n - H_{n-1}}{\left(\frac{Q_D}{D}\right) + h_D - h_{n+1}}$$

$$\frac{D}{v_n} = 0.2858$$

$$\frac{L_{n-1}}{V_n} = 1 - \frac{D}{v_n}$$

$$\frac{L_{n-1}}{V_n} = 0.715$$

Operating line for upper section,
$Y_n = 0.715x_{n-1} + (0.2858)(0.98)$
$Y_n = 0.715x_{n-1} + 0.28$

E. Finding amount of vapour content in the outlet stream from bottom.

$$\frac{B}{v_m} = \frac{H_m - H_{m-1}}{\left(\frac{Q_B}{B}\right) + h_B - h_{m+1}}$$

$$\frac{B}{v_m} = 0.077$$

$$\frac{L}{v_m} = 0.92214$$

Operating line for stripping section.

$$Y_m = 1.077\, x_{m+1} - 0.0038$$

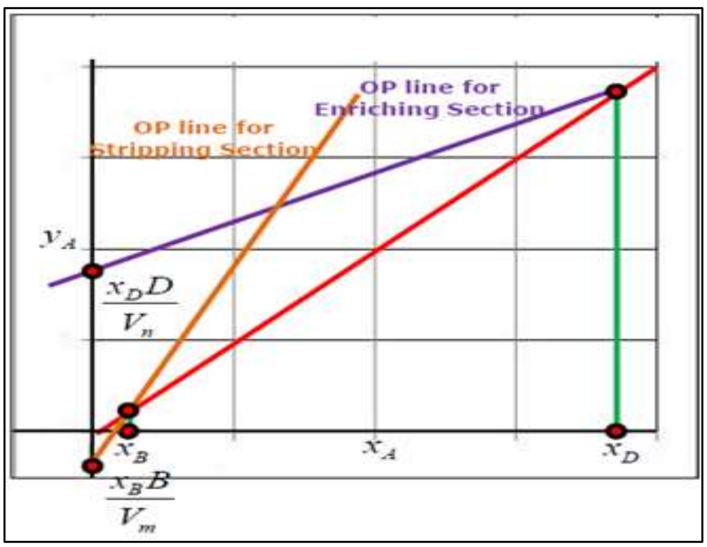
Finding state and composition of inlet liquid stream.

$$q = \frac{H - h_f}{H - h}$$

q = 0.831
If
q >1 liquid stream is sub cooled
q = 1 saturated liquid feed
q<1 two phase mixture feed
q=0 saturated vapour feed
q<0 superheated vapour feed

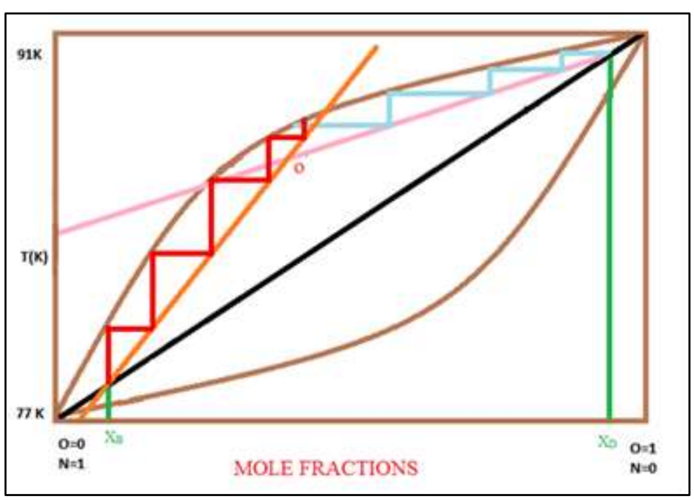
On plotting these lines onto the graph, it gives the following results. And we know the feed conditions by the intersection of these lines.

F. Feed condition



G. Finding Theoretical Numbers of Plates.

1) (Mc-Cabe Thiele Method)



– Dimention Of Coil At Boiler

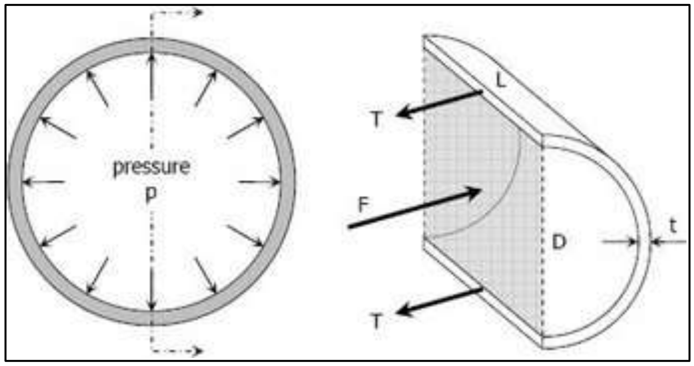
$$\dot{Q} = \dot{m} \cdot C_P \cdot dT$$

$$kW = \frac{kg}{s} \cdot \frac{kJ}{kg \cdot {}^{\circ}C} \cdot {}^{\circ}C$$

– Thickness Of The Shell

$$\sigma_h := \frac{p \cdot d}{2 \cdot t}$$

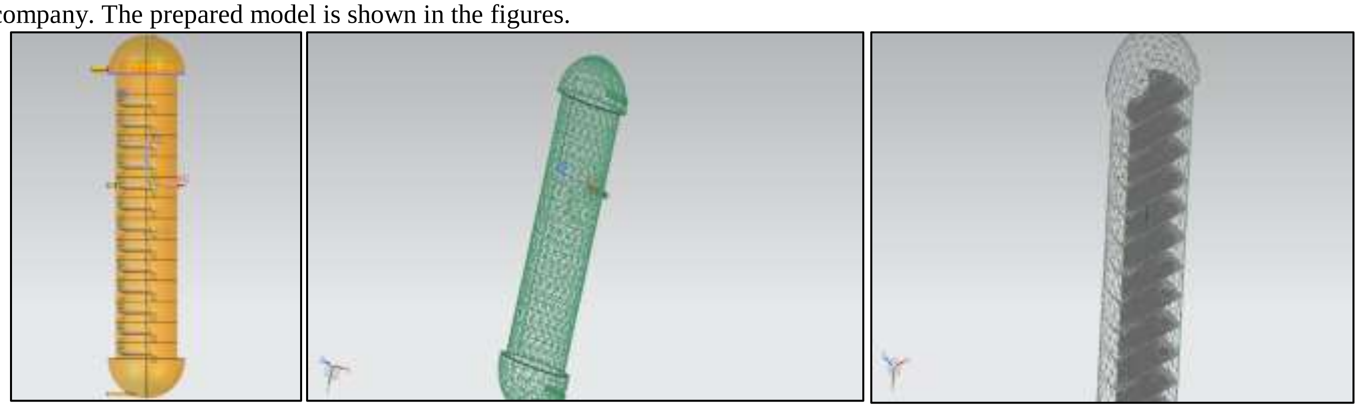
$$\sigma_L = \frac{pd}{4t}$$



H. Modelling and Analysis

Sr. No.	PARAMETER	DIMENSIONS
1	OUTER DIAMETER OF SHELL	1264 mm
2	DIAMETER OF PLATE	1200 mm
3	SPACING OF PLATE	304 mm
4	THICKNESS OF SHELL	32 mm
5	THICKNESS OF PLATES	4 mm
6	DIAMETER OF HOLES	1 mm
7	SPACING BETWEEN HOLES	5 mm
8	EFFECTIVE AREA FOR HEAT TRANSFER	101787602mm^2
9	DOWNCOMMER DIAMETER	80mm
10	TRANSFER PIPES DIAMETER	19mm

According to the dimensions, the model was prepared in the Siemens-NX software available at the cad laboratory of LD College of engineering. This model was prepared in 3-dimentions with the guidance of the trainers from the design-tech company. The prepared model is shown in the figures.



I. Boundary Conditions for Analysis:

1) *Inlet air stream(in liquid form) :*
   – Temperature : 91k
   – Pressure 510 kpa
   – Feed rate : 48.94 mol s^{-1}
2) *Stream condition after passing through reboiler*
   – Temperature : 86k

  - Pressure 507 kpa
  - Feed rate : 48.94 mol s^{-1}

3) *Stream after passing through joule thomson expansion valve*
  - Temperature : 80.50k
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4) *Heat to Be Extracted From Condenser (Q_c)*
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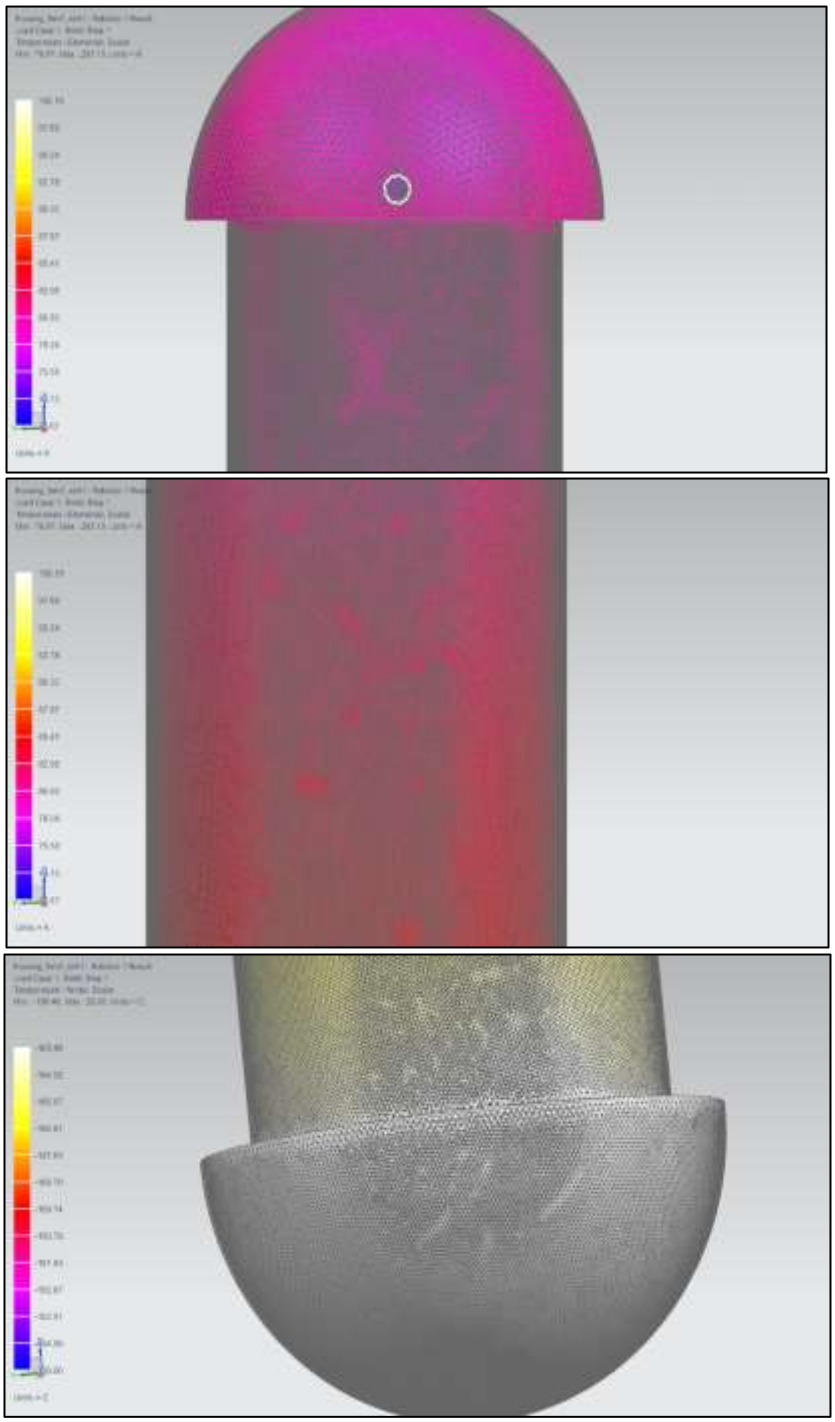
III. RESULTS AND DISCUSSION



The liquefaction of air is used to obtain nitrogen, oxygen, and argon and other atmospheric noble gases by separating the air components by fractional distillation in a cryogenic air separation unit. There is need to design the whole system which is tight integration of number of heat exchangers and various other cryogenic devices. By correctly designing and obtaining correct design operating conditions, we can save a lot of amount of power in form of heat inleaks, by providing suitable insulations.

Also, we observe from this dissertation work that, not only in the cryogenic separation but also in other cryogenic processes, the design and selection procedure of insulation is very critical and should be done very carefully. Further, it was observed that when the requirement of LN_2 and LO_2 are in large amount, then cryogenic distillation is the most preferrable process.

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