



iJRASET

International Journal For Research in
Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 5 Issue: VIII Month of publication: August 2017

DOI: <http://doi.org/10.22214/ijraset.2017.8283>

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Design of 100TPD Oxygen Plant & Thermal Analysis

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Abstract: For the Designing of 100TPD oxygen plant requires separate designing of distillation unit and condenser. Oxygen gas is commonly used in steel plant, medical field, blast furnace etc. This process is convenient because the raw material is available at no cost and in limitless amounts. Oxygen plant consists of number of unit operation like compressors, heat exchanger, distillation column, expansion turbine etc. The final objective is to separate oxygen from air at desired purity requiring minimum cost. The purity of oxygen over 99.5% is required for welding, cutting and medical application. In order to minimize the costs, heat integration is used throughout the process. A column is designed to maintain product purity and reject disturbances. The effect of product quantities and purities on the selection of process cycle is discussed and general design guidelines are given. Another methods such as membrane (up to about 40% oxygen), pressure swing adsorption (PSA) and vacuum pressure swing adsorption (85-95% oxygen) are commercially used to separate oxygen from ordinary air. High purity oxygen requires cryogenic distillation. The primary hazards in oxygen plant are fire hazards which are mainly focused. Any industrial process that generates or uses oxygen is exposed to an elevated risk of fire. This applies in particular to oxygen plant, where the presence of oxygen obviously increases fire hazards. Mechanism such as friction, Mechanical impact and organic material non-compatible with oxygen can quickly spark a fire inside valves, for instance. In the presence of oxygen, any flammable material once ignited will readily burn. The important requirements for safely handling oxygen plant within air separation facility.

Keywords: Suction filter, compression, Adsorption, Expansion, Air cooling tower, water cooling tower and Distillation.

I. INTRODUCTION

Oxygen present in the air has a wide range of application in several industries like steel industry, aeronautical industry, medical industries [1]

A. Types of Separation Technique

Mainly three types of air separation techniques are used that are (a) Distillation, (b) Adsorption and (c) Membranes [2]. Distillation technique is the most convenient and efficient of the three technologies. And able to produce for high purities greater than (99%) and large scale production [3].

B. The Basic Steps for Separation of Oxygen from Air are Described as

- 1) **Cleaning of Air:** Before taking the air in compressor it is cleaned by suction filter.
- 2) **Compression of Air:** Ambient air which is cleaned in filter is compressed to approx. 6 bars by compressor. In compressor, air enters in an axial direction to the impeller, which is attached to the shaft with a bearing and rotates at high speed. This causes the air to rotate.
- 3) **Precooling of Air:** To separate oxygen from air, it must be liquefied at extremely low temperature. The compressed air is pre-cooled with chilled water.
- 4) **Purification of Air:** Impurities such as water vapour and carbon dioxide are then removed from the air in so-called molecular sieve. These are manufactured from a man made mineral of aluminium silicate called zeolite [4] [5].
- 5) **Cooling of Air:** Because the gases which make up air only at very low temperatures, the impurities removed air in the main heat exchanger cools to about. -175°C .
- 6) **Separation of Oxygen from Air:** The difference in boiling points of the constituents is exploited for the separation process. The continuous evaporation and condensation brought about by the intense exchange of matter and heat between the rising steam and the descending liquid produces pure nitrogen at the top of the low-pressure column and pure oxygen at the bottom [4]

- 7) *Reflux*: Reflux is a technique involving the condensation of vapours and the return of this condensate to the system from which it originated. It is used in industrial distillations.

Table 1 Composition Of Dry Air [4]

Name of gases	Volume (%)	Boiling point
Nitrogen (N ₂)	78.08%	-195.80
Oxygen (O ₂)	20.95%	-183.00
Argon (Ar)	0.93%	-185.90
Helium (He)	0.005%	-268.90
Neon (Ne)	0.0018%	-246.10
Krypton (Kr)	0.00011%	-153.20
Xenon (Xe)	0.000009%	-108.00

II. METHODOLOGY

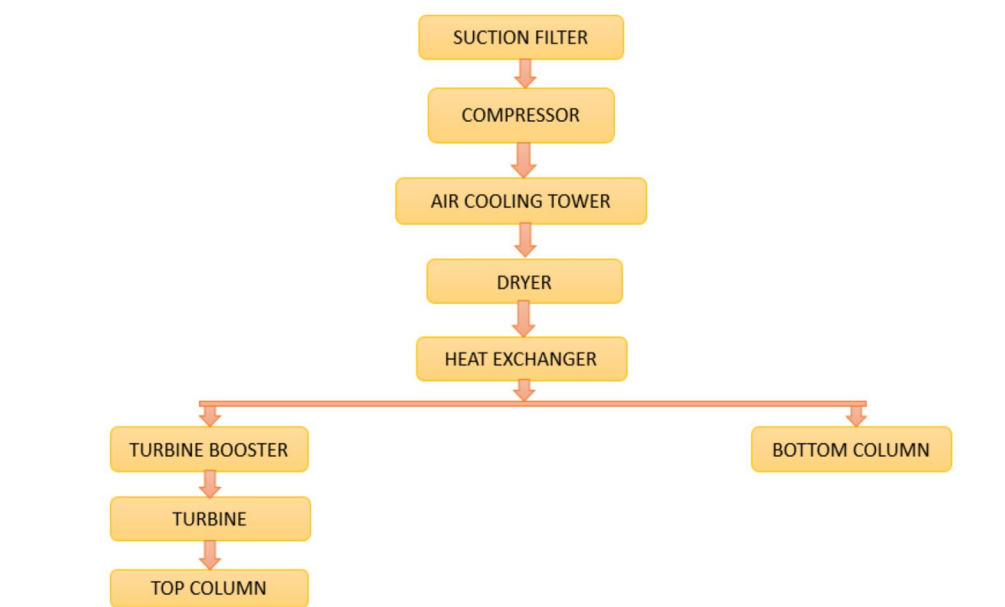


Fig. 1 Methodology

A. Suction Filter

It is used for cleaning the air before enter the compressor.

B. Compressor

Compressor which uses a drive motor to power the device, which sucks in successive volume of air from the atmosphere, compresses each volume of air in a limited space to increase the pressure, resulting in a small amount, and then transfers the air at high pressure.

C. Air Cooling Tower

The cooling of air to the mole sieves is now a days most often done with the spray cooler. This consists of a column of filler medium, where the cooling water goes in at the middle and extraction cooled water at the top. The air enters at the bottom counter current to water and cooled air goes out at the top. Consequently air is cooled by direct contact with water.

$$\square\square \text{ Vaporisation} = 1100(\text{KG/HR}) \times 2460(\text{KJ/KG}) \\ = 2706\text{MJ/HR}$$

$$\square\square \text{ Water cooling} = 45431(\text{KG/HR}) \times (22-10) (\text{Deg. C}) \times 4.19(\text{KJ/KG Deg. C}) = 2284\text{MJ/HR}$$

$$\square \square \text{ GAN Cooling} = 73976 \text{ (KG/HR)} \times (25-20) \text{ (Deg. C)} \times 1.04 \text{ (KJ/KG Deg. C)}$$

$$= 385 \text{ MJ/HR}$$

$$1) \text{ Withdrawn heat} = 2669 \text{ MJ/HR} [3]$$

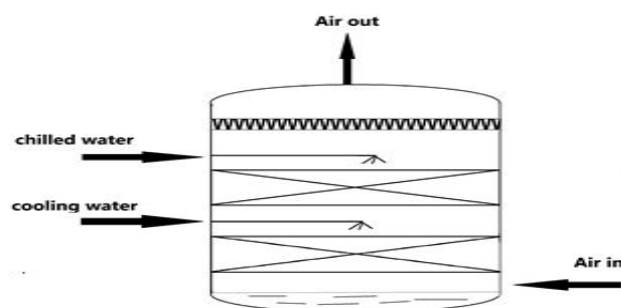


Fig. 2 Air cooling tower

D. Dryer

It is used for removing the different impurities from the air. Here There is two Molecular sieve drier. One is in line and other is in regeneration.[5]

E. Heat Exchanger

It is plate type heat exchanger in which purified air coming from post filters is sent directly to the main exchanger line where it exchange heat with expanded gas. Expanded gas removes the heat energy from warmer stream.

F. Expansion Turbine

Expansion turbines are used to produce cold. This gives mechanical work that can be used by impeller on the same shaft to compress the gas, a booster.

G. Distilled Column

It is distillation column combined from bottom column, condenser and re boiler and upper column .Bottom column work under 5.5-6.5 at pressure. The saturated air is introduced into high pressure column (HP column) to be separated into oxygen – rich liquefied air and liquefied nitrogen. The liquefied air and liquefied nitrogen are supplied into low pressure column (LP Column) as reflux fluids and are separated into highly-pure oxygen and nitrogen [6].

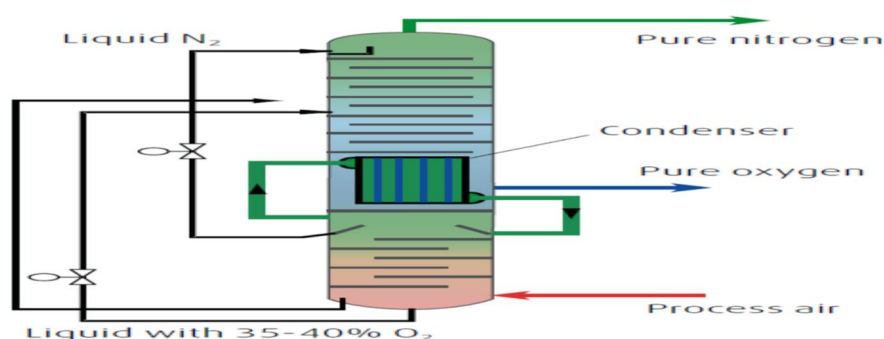


Fig. 3 Distillation Column[7]

Table 2: Process Parameter

	Temp. In °C	Pr. In Kg/cm ²	Flow M ³ /hr
Compressor outlet	90	5	17800
After ACT	10 to 15	5	17800
Air inlet of column	-169 to -173	5	13800
Turbine inlet	-121 to -125	5	4000

Turbine outlet	-167 to -171	0.5	4000
Top column	-169 to -192	0.5	
Bottom column	-169 to -170	5	

III. EQUIPMENT DESIGN CALCULATION

A. Mass and Energy Balance

Capacity of the plant is 100 Ton/day of gases oxygen of 99.95% purity

Total oxygen production= 100 Ton/day

$$= (100 \times 1000) / (24 \times 32)$$

$$= 130.20 \text{ kg moles/Hr.}$$

At standard temperature and pressure,

1kg.mole occupies 22.4M³

Oxygen produced in volumetric units = 130.20 × 22.40

$$= 3000 \text{ m}^3/\text{Hr.}$$

B. Quantity of Intake Air

$$1) \text{ Capacity of the unit} = 3000 \text{ M}^3/\text{Hr}$$

$$2) \text{ Volume \% of oxygen in the air} = 21\%$$

$$3) \text{ Quantity of air needed} = 3000 / 0.21$$

$$= 14285 \text{ m}^3/\text{Hr}$$

Assuming about 25% less of air due to removal of moisture, CO₂, instrument air and from possible leaks.

Quantity of air needed = 14285 + 14285 × 0.25 = 17800 M³/hr.

(Atmospheric Condition Temp. = 30°C, Relative humidity = 60%)

Table 3: Vertical Lines Coordinate Under Equilibrium Curve

x	y		x	y		x	y
0.02	0		0.49	0.54		0.89	0.92
0.02	0.05		0.49	0.7		0.89	0.94
0.04	0.05		0.64	0.7		0.92	0.94
0.04	0.1		0.64	0.81		0.92	0.96
0.09	0.1		0.73	0.81		0.96	0.96
0.09	0.2		0.73	0.86		0.96	0.98
0.18	0.2		0.78	0.86		0.98	0.98
0.18	0.36		0.78	0.9			
0.32	0.36		0.843	0.9			
0.32	0.54		0.843	0.92			

Table 4: On Feed Line, Distillation Line And Horizontal Coordinate Under Equilibrium Curve

Feed line			Distillation line			Horizontal line coordinate under equilibrium curve					
x	y		x	y		X	y		x	y	
0.78	0		0.98	0		0.02	0.05		0.32	0.54	
0.78	0.2		0.98	0.2		0.04	0.05		0.49	0.54	
									0.843	0.9	

0.78	0.3		0.98	0.4									
0.78	0.4		0.98	0.6		0.04	0.1			0.49	0.7		0.843 0.92
0.78	0.5		0.98	0.8		0.09	0.1			0.64	0.7		0.89 0.92
0.78	0.98		0.98	0.98									
						0.09	0.2			0.64	0.81		0.89 0.94
						0.18	0.2			0.73	0.81		0.92 0.94
						0.18	0.36			0.73	0.86		0.92 0.96
										0.78	0.86		0.96 0.96
												0.96	0.98

TABLE 5: On Vapour- Liquid Equilibrium, Rectifying Operating Line, Stripping Line And Diagonal

Vapour –liquid equilibrium relationship $Y = \alpha x/1 +(\alpha-1)x$			Rectifying operating line 0, $X_d/R_{min} +1$			Stripping line by connecting intersection point of q-line and operating line of rectifying line			Diagonal($y=x$)	
x	y		x	y		x	y		0	0
0	0		0	0.4		0.04	0.41		0.1	0.1
0.02	0.05		0.1	0.46		0.09	0.1		0.2	0.2
0.04	0.1		0.2	0.52		0.18	0.2		0.3	0.3
0.09	0.2		0.3	0.58		0.32	0.36		0.4	0.4
0.18	0.36		0.4	0.64		0.49	0.54		0.5	0.5
0.32	0.54		0.44	0.66		0.64	0.7		0.6	0.6
0.49	0.7		0.54	0.72		0.734	0.801		0.7	0.7
0.64	0.81		0.6	0.76		0.78	0.86		0.8	0.8
0.73	0.87		0.72	0.83					0.9	0.9
0.78	0.9		0.78	0.865						
0.842	0.93		0.84	0.9						
0.885	0.95		0.92	0.94						
0.92	0.965		0.98	0.98						
0.96	0.98									

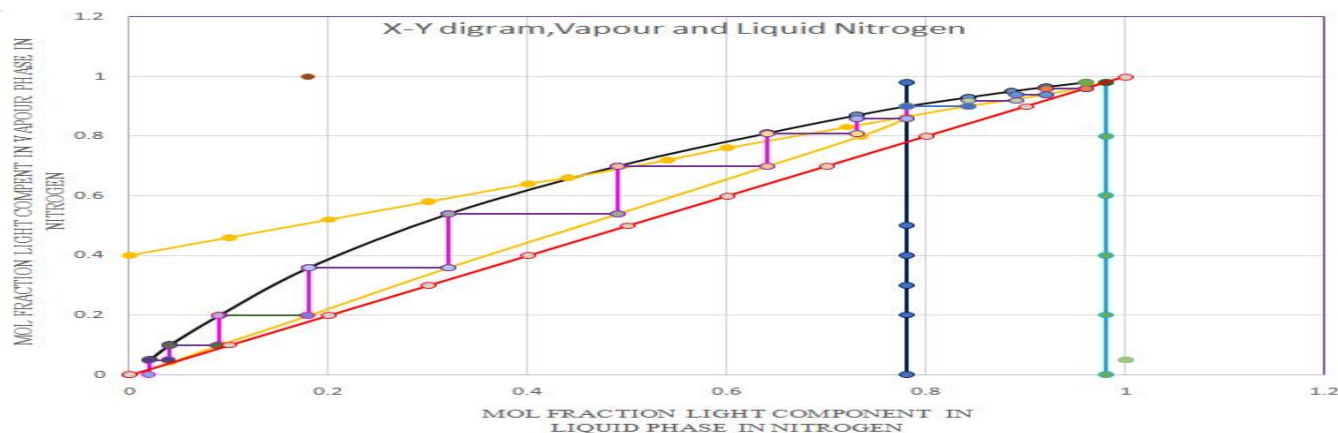


Fig. 4 Vapour and liquid phase of nitrogen

C. Mechanical Calculation

1) Step 1 Mass Balance and Determination of Theoretical Plates:

TABLE 6: Mole Fraction Of Feed And Product

Component	Feed mole fraction	Top product mole fraction	Bottom product mole fraction
	0.79(N_2)	0.99	0.96(N_2)
Air	0.21(O_2)	0.01	0.04(O_2)

a) *Relative Volatility (α)*: It is a measure of differences in volatility between two components and hence their boiling points.

Average relative volatility $\alpha = (Y_a / X_a) / (Y_b / X_b)$

$$= 1.58$$

Where, Y_a = Mole fraction of N_2 in Vapour phase (0.79)

X_a = Mole fraction of O_2 in liquid phase (0.35)

Y_b = Mole fraction of N_2 in liquid phase (0.65)

X_b = Mole fraction of O_2 In vapour phase (0.21)

$X_{d1}=0.99$, $X_{d2}=0.01$, $X_{b1}=0.04$, $X_{b2}=0.96$

Number of plates = N

b) *From Underwood Fenske Equation:*

$$N = \frac{\log(c_1)}{\log(\alpha)} + \frac{\log(c_2)}{\log(\alpha)}$$

$$= \frac{\log(0.99)}{\log(1.58)} + \frac{\log 24}{\log(1.58)}$$

$$= 4.5951 / 0.4574 + 3.178 / 0.4574$$

$$= 10.046 + 6.94$$

$$= 17$$

Where, μ of liquid O_2 = 0.19Cp

μ of liquid N_2 = 0.24Cp = μ is the average molar

Viscosity of feed in Cp = 2.67

$$\text{Average molar } \mu \text{ of feed} = 0.79 \times 0.24 + 0.21 \times 0.19$$

$$= 0.2295 \text{Cp}$$

$$= 0.6127$$

$$\square \square \text{ Actual no. of plate} = 17 / 0.6127 = 28$$

$$\square \square \text{ From the graph feed enters at 15th plate.}$$

$$\square \square \text{ Actual plate at which feed enters} = 15 / 0.6127 = 24$$

2) Step 2 Calculation of Minimum Reflux Ratio to Control Temp. & Purity:

$$\square \square R_m = 1/X_f (\alpha - 1) = 1/0.78(1.58 - 1) \\ = 2.21$$

$$\square \square \text{Actual reflux ratio} = 2.5 \times R_m [14] \quad (\text{As per NPTEL IIT}) \\ = 2.5 \times 2.21 \\ = 5.525$$

3) Step 3 Column Pressure :

$$\square \square \text{Top Column Pressure} = 0.5 \text{ Kg/cm}^2$$

$$\square \square \text{Bottom column Pressure} = 5 \text{ Kg/cm}^2$$

$$\square \square \text{Pressure drop per Tray} = 0.166 \text{ Kg/cm}^2$$

4) Step 4 Plate Spacing

Length = 300mm is assumed.

5) Step 5 Calculation of Column Diameter (D) :

$$\square \square P = \rho L R T_1 \quad \text{Where,} \\ \square \square 50000 = \rho L \times 287 \times 103 \quad P = \text{Pressure of air} = 5 \text{ Kg/cm}^2 \\ \square \square \rho L = 50000/287 \times 103 \quad \rho L = \text{Density of Air Liquid.} \\ \square \square \rho L = 1.691 \text{ Kg} \times \text{Kg K/m}^2 \text{ JK} \quad R = \text{Characteristics gas constant} \\ \square \square \rho L = 16.59 \text{ Kg/m}^3 \quad T_1 = \text{Temperature of Air} = -170^\circ \text{C} \\ \square \square \rho L = 16.59 \text{ Kg/m}^3 = 103 \text{ K} \quad T_2 = \text{Temperature of Air Vapour } 15^\circ \text{C} = 288 \text{ K} \\ \square \square P = \rho V R T_2 \quad \rho V = \text{Density of Air vapour.} \\ \square \square \rho V = 50000/287 \times 288 \\ \square \square \rho V = 0.6049 \text{ Kg} \times \text{Kg K/m}^2 \text{ JK} \\ \rho V = 5.93 \text{ Kg/m}^3$$

a) From the Souder-Brown Ernest E. Ludwig, Louisiana Page no.66:

Maximum allowable mass Velocity [10]

$$\square \square W = C [(\rho L - \rho V)]^{1/2} \\ \square \square W = 1.15 [5.93(16.59 - 5.93)]^{1/2} \\ \square \square W = 1.15 [5.93(16.59 - 5.93)]^{1/2}$$

$$i) \quad W = 9.332 \\ ii) \quad D = \left[\frac{4}{\pi} (V/W) \right]^{1/2} \\ iii) \quad D = 2 \text{ M}$$

Where, W = Maximum Allowable Mass velocity through Column Using bubble Cap trays.

C = Factor related to entrainment

$$V = \text{Vapour flow rate} = 17800 \text{ m}^3/\text{hr} \\ = 4.94 \text{ m}^3/\text{sec} \\ = 29.320 \text{ Kg/sec}$$

b) From the Table of Ernest E. Ludwig Page no. 87

6) Step - 6 Design of Tray:

Tray types

Bubble Cap.

Sieve Tray or Perforated Tray with down comer.

Perforated Plate without down comer

Total area, sq.ft. = 33.18 ft²

Liquid Flow = Cross

No. of Down flow Weir = One

No. of Down flow Seal = one

No. of caps & Riser/Tray = 150

No. of Rows/Tray = 12

Total slot Area = $9.64 ft_2$

Percent of Tower Area = 29.1

Total Riser area = $5.56 ft_2$

Percent of Tower Area = 16.75

Overflow Weir Length = 4.31ft

Percent of Tower Dia. = 66

Down flow segment Area

Maximum Area = $2.39 ft_2$

Maximum Area = $1.027 ft_2$

Under flow clearance = 3 inch.

Under flow Area = $0.750 ft_2$

Up flow area = $0.882 ft_2$

a) *Nominal Size for Bubble –cap:*

4-10 ft. towers 4 inches.

Pitch space 1-3 inch.

Skirt height 0.25 – 1.5 inches

7) *Clearance :*

Cap to tower wall 1.5 inch minimum.

Cap to weir 3 inch minimum.

Cap to down comer 3 inch.

Drain hole size 3/8 – 5/8 inch

Liquid height $300mm/2 = 150mm = 15cm = 5.90$ inch

8) *Step -8 Determine the Height of Column:*

Formula assumes that a spacing of two feet between tray.

$$\begin{aligned} H &= 2.3 NA[13] && \text{as per Douglas} \\ &= 2.3 \times 28 + \text{Height of condenser} \\ &= 65 + 6 \\ &= 71' = 22 M \end{aligned}$$

D. Thermal Analysis

Thermal analysis is performed with the help of Exergy analysis. Exergy is the best concept to carry out energy – efficiency study. It is defined as the maximum work that can be derived from a reversible system. In other words exergy indicate how much system is helpful corresponding to work input.

$$E_x = (H - H_0) - T_0(S - S_0) \dots \dots \dots (I)$$

A process depends

$$\Delta S = \Delta H \{ [\text{Log } (T_2 / T_1)] / (T_2 - T_1) \} \dots \dots \dots (II)$$

If gaseous pressure changes occur

$$\Delta S = [(C_p dt) / T] - [(R \Delta P) / P] \dots \dots \dots (III)$$

And it follows that

$$\Delta S = \Delta H \{ [\text{Log } (T_2 / T_1)] / T_2 / T_1 \} - R \text{Log } (P_2 / P_1) \dots \dots \dots (IV)$$

An irreversible process is one in which the potential for doing work is lost and it can be shown that

$$\sum E_x(\text{in}) = E_x(\text{out}) + E_x(\text{irreversible}) \dots \dots \dots (V)$$

E. Exergy Efficiency

It is the ratio of the total energy leaving to the total energy entering in the control volume.

$$\eta = (\text{Exergy})_{\text{out}} / (\text{Exergy})_{\text{in}}$$

F. Properties of Air

The critical temperature of air is 132.6 K (-140.55°C) at 37.66 bar (3766kpa) absolute. Above this temperature air cannot be liquefied by pressure alone. The following formula is used for liquefaction of air.

For the beginning of liquefaction

$$\text{Log } p \text{ (bar)} = 4.640 - 0.458 (1000 / T_k) + 0.00733 (1000 / T_k)^2 \dots \dots \text{(VI)}$$

For the completion of liquefaction

$$\text{Log } p \text{ (bar)} = 4.7640 - 0.476 (1000 / T_k) + 0.00733 (1000 / T_k)^2 \dots \dots \text{(VII) [11]}$$

G. Specific Power

It is ratio of total power consumed by the plant to the total oxygen produced

Here Total power consumption in equipment in one day = 60000Kw

Total oxygen produced in one day = 70000m³

Specific power = 60000/70000 = 0.85Kw/m³

H. Contribution of Total Power

Item	%
Air compressor and motor	31
Expansion turbine	01
Heat exchanger	16
Pressure drop	05.5
Pressure reducing Valve	03.3
Heat leak	00.9
Mixing	00.4
HP (Lower Column)	03.3
LP (Upper Column)	16.7
Ideal work of separation	16.9
Product condition	5.0
Work input	100 [8]

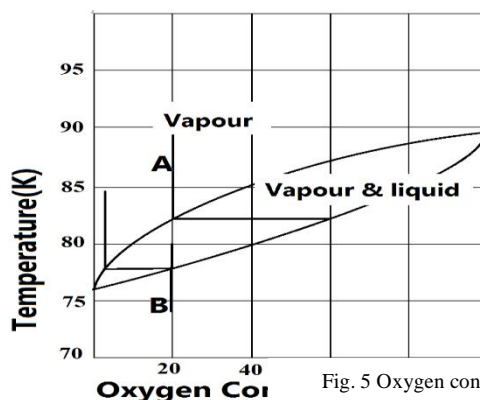


Fig. 5 Oxygen concentration between temperatures

IV. RESULT & DISCUSSION

These results are below

- The rational exergy efficiency of compressor and booster are found as 64.39% and 63.05% respectively.
- The rational exergy efficiency of main heat exchanger and sub cooler is obtained as 56.41% and 86.72% respectively.
- The rational exergy efficiency of HP and LP distillation column is obtained as 49.71% and 53.85% respectively.

If, we increase the quantity of air fed to the column a larger quantity of nitrogen will require to condense. The rate of condensation in the condenser is not sufficient for this larger quantity and if the gas does not condense the pressure rises. Higher pressure means that the condensation temperature is higher and therefore it follows that the temperature difference ΔT rises, until the condensation of the condenser is sufficient again to condense all of the nitrogen. Liquid Nitrogen purity solely depends on reflux ratio. All incoming air is in gaseous form, which completely condenses, the Liquid Nitrogen purity solely depends on how much is taken out from the Lower column.

V. CONCLUSION

Thermal analysis is important for proper utilisation of energy. Through this we can focus on exergy loss and improve with taking proper step. Otherwise specific power will increase. As the result production cost of oxygen will also increase.

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