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Modification of Design of Cryo-Oxygen Plant for Improved Performance

Rama Rao T[1*] and Ranjan Ojha P[2]

[1]*Professor Mechanical Engineering Deptt, Bhilai Institute of Technology Raipur, CG, India, 496331*

[2]*UG Scholar 8th Sem. Mechanical Engineering Deptt, Bhilai Institute of Technology Raipur, CG, India, 496331*

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***Corresponding author:** Rama Rao T, Professor Mechanical Engineering Deptt, Bhilai Institute of Technology Raipur, CG, India, 496331, Tel: +917898351444; E-mail: tramarao.bit@gmail.com*

Abstract

Development of an industry is very important for the nation and so is its economical functioning. Cryogenics, being versatile in its application needs proper nourishment and care, which is done by periodic improvements in its systems. Specifically liquid Oxygen is a very important item for high level research and applications. The possibility of launching space vehicle has also come due to the development of liquid oxygen. This also finds its use as a lifesaving item for doctors and many more. The necessity for the economic development of these plants will benefit mankind in many fields. There are many researches which has been done starting from reducing the cost of Oxygen Liquefaction and ultimately its production for cryogenics. The only expenditure for production of liquid Oxygen is electricity. Out of the total electricity consumed, compressor consumes 90% and the remaining 10% is used in running other machinery and lighting of the plants. Studies have also led to the fact that the temperature also plays a great role in consumption of electricity. So in this paper, an attempt has been done to reduce this temperature also. We have incorporated a solar refrigeration system and Freon cooler. Booster compressor is also introduced and modification in it has led to the work saving up to 4.30%.

Keywords: Cryogenics; Liquefaction; Solar Refrigeration System; Freon cooler; Booster Compressor;

Introduction

The subject of Cryogenics is very broad in scope and hence it is necessary to limit the field to be considered. The term cryogenics means, literally, the production of icy cold. It is also used as a synonym for low temperature, which involves temperatures below -150 °C. The boiling points of so called permanent gases, such as helium, hydrogen, neon, nitrogen, oxygen and air, lie below -150°C, while the froe refrigerants, hydrogen sulphide, and other common refrigerants all boil at temperature above -150°C. Cryogenics engineering is the field of developing and improving low temperature technique, process and equipment. It includes the practical utilization of low temperature phenomena. [5] The cryogenics has a diversified application in the vital field of engineering and its productions are increasing yearly. Some areas involving cryogenic engineering are:

- **Rocket propulsion system:** Liquid oxygen is used as oxidizer during combustion.

- **Studies in high energy physics:** Liquid hydrogen is used in detection and study of high energy particles.

- **Nuclear engineering applications:** Preparation of Heavy ice, maintaining cryogenic temperatures for neutron bombardment, etc.

- **Electronics:** Controlling voltage fluctuation, noise and maintaining suitable operating temperature.

- **Gyroscopes:** Superconducting gyro works in a high vacuum, where support friction, wind age friction, problem of bearing instability, and dimensional instability as due to superconductivity the thermal expansion coefficient of materials approaches zero and hence practically all these problems are eliminated.

- **Biology and medicine:** Used in cryobiology and cryosurgery, as a killing agent in food preservation, preservation of biological materials likes blood, tissue and bone marrow. Also freezing techniques have been used in the treatment of eye surgery and inner ear surgery.

- **Space simulation:** Creation of simulation chamber for testing components for mission.

- **Manufacturing process:** Used in steel manufacturing process, open hearth furnace, CO formation and space vehicle power plant.

There are significant effects on certain properties of materials which is of great importance, like:

- **Mechanical properties:** Yield stress, Ultimate stress and Hardness for alloys and some other materials would increase with the decrease in temperature.

- **Thermal Properties:** Thermal conductivity of alloys and impure metals, specific heats of liquids and solids and coefficient of thermal expansion decreases with the decrease in temperature.

- **Electrical properties:** At very low temperatures, simultaneous disappearance of all electrical resistance and appearance of perfect diamagnetism takes place. In the absence

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of magnetic field, many elements, alloy and compounds become super conducting at a fairly well defined temperature called transition temperature in zero field.

Specifically focusing on the field of research, end product here is Oxygen. The liquid oxygen has characteristic blue colour, which is caused either by the presence of the polymer or long chain molecule or by the unpaired electrons which are responsible for Para magnetism in liquid oxygen. At 1 atm pressure, liquid oxygen boils at 90.2 K and freezes at 54.4 K. Saturated liquid oxygen at 1 atm is dense than water at 60 °F. Liquid oxygen is slightly magnetic in contrast to the other cryogenic fluids, which are non-magnetic. Hence by measuring magnetic susceptibility, small amount of oxygen may be detected in mixture of other gases. Liquid oxygen is chemically reactive, especially with hydrocarbons. Because of its chemical activity, oxygen presents a safety problem in handling.

Looking to the available isotopes we can conclude that Oxygen has only three stable isotopes of mass numbers 16, 17 and 18. The relative abundance of these three isotopes is 10000:4:20 or 99.76%, 0.04% and 0.20% respectively. The manufacture of liquid oxygen in large quantities is done by distillation of liquid air, since the oxygen is the second most abundant substance in air (20.95% by volume and 23.20% by weight) (Table 1) [1].

Principle of Air Separation

The basic principle of an air separation plant is liquefaction of air and separation of its constituents by rectification. As the liquefaction of air is concerned to Cryogenic engineering, and there has been a great amount of work devoted to improve the efficiency of air separation plant. As the major source for manufacture of industrial gases (Oxygen, nitrogen and rare gases) is air and commercial importance of these industrial gases are known to us. The demand of Oxygen is comparatively more than other industrial gases. Attempts are to develop Oxygen economically with desirable purity, i.e. with lesser power consuming and equipment of high precision. As the raw material, cost of producing Oxygen is nil and only requirement is electrical energy. [2] Hence by using proper Cryogenic techniques we can reduce electrical usage. Focusing on the air components, for

Table 1: Isotopes of Oxygen

nuclide symbol	Z(p)	N(n)	isotopic mass (u)	half-life	decay mode(s)[16]	daughter isotope(s)[n 1]	nuclear spin	representative isotopic composition (mole fraction)	range of natural variation (mole fraction)
^{12}O	8	4	12.034405(20)	$580(30)\times10^{-24}$ s [0.40(25) MeV]	2p (60.0%)	^{10}C	0+		
					p (40.0%)	^{11}N			
^{13}O	8	5	13.024812(10)	8.58(5) ms	β^+ (89.1%)	^{13}N	(3/2−)		
					β^+, p (10.9%)	^{12}C			
^{14}O	8	6	14.00859625(12)	70.598(18) s	β^+	^{14}N	0+		
^{15}O	8	7	15.0030656(5)	122.24(16) s	β^+	^{15}N	1/2−		
^{16}O[n 2]	8	8	15.99491461956(16)	Stable			0+	0.99757(16)	0.99738–0.99776
^{17}O[n 3]	8	9	16.99913170(12)	Stable			5/2+	$3.8(1)\times10^{-4}$	3.7×10^{-4}–4.0×10^{-4}
^{18}O[n 2][n 4]	8	10	17.9991610(7)	Stable			0+	$2.05(14)\times10^{-3}$	1.88×10^{-3}–2.22×10^{-3}
^{19}O	8	11	19.003580(3)	26.464(9) s	β^-	^{19}F	5/2+		
^{20}O	8	12	20.0040767(12)	13.51(5) s	β^-	^{20}F	0+		
^{21}O	8	13	21.008656(13)	3.42(10) s	β^-	^{21}F	(1/2,3/2,5/2)+		
^{22}O	8	14	22.00997(6)	2.25(15) s	β^- (78.0%)	^{22}F	0+		
					β^-, n (22.0%)	^{21}F			
^{23}O	8	15	23.01569(13)	82(37) ms	β^-, n (57.99%)	^{22}F	1/2+#		
					β^- (42.0%)	^{23}F			
^{24}O	8	16	24.02047(25)	65(5) ms	β^-, n (57.99%)	^{23}F	0+		
					β^- (42.01%)	^{24}F			

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simplicity air will be considered to be a binary mixture of 21% of Oxygen and 79% of Nitrogen, moreover the air introduced to the separation process is kept free from CO_2 and water vapour, but it does contain 0.93% of Argon. It's true that presence of Argon is complicated and cannot be ignored, but for understanding the fundamentals of air separation we ignore this added complication. Other gases like Helium, Neon, Krypton and Xenon are present in small quantities and have boiling points so far removed from those of Oxygen and Nitrogen that they introduce no important complications (Table 2) [6,12].

Table 2: Typical impurities in Air (ppm)

Impurity	Normal	Maximum
Water	-	Saturated
Carbon dioxide	350	1000
Acetylene	0.1	1
Ethylene	0.01	200
Propylene	-	0.2
Methane	2.5	10
Butane	-	0.1
Carbon mono-oxide	-	0.05
Sulphur compounds	-	0.1

The simplest form of air separation plant was the originals single column lined cycle plant which was first operated in 1902; here is a brief classification according to the following basis:

• **Size:** Small plants (producing less than 750 cu.M/hr) and Tonnage plants (producing more than 750 cu.M/hr)

• **Operating Pressure:** High pressure plant (more than 35 bar), Medium pressure plant (6-35 bar) and Low pressure plant (5-6 bar)

• **Process cycled:** Cryogenic plants and Non-cryogenic plants or PSA plants

• **Type of expansion:** Free expansion or J-T expansion type plants and Expansion engine type plants

• **Rectification column:** Single column and Double column plants

In air separation plant, cooling it until its condensation temperature is reached and then removing the latent heat of vaporization accomplish the liquefaction of air. Thus a suitable refrigeration process creates perfect air liquefaction (Figure 1), which varies to the practical methods. The separation of mixture of gases is an important aspect of cryogenic engineering and is usually achieved by fractional distillation. Industrially, the two most important processes are separation of component of air and the modification of the composition of natural gas.

To illustrate the principle let us take separation of air, which will be treatment as mixture of 21% of Oxygen and 79% of Nitrogen only. The ideal work WR per mole required to separate a mixture of perfect gases into its components at a temperature T may be calculated from the entropy of mixing, remembering that for a perfect gas, the internal energy is a function of temperature only.

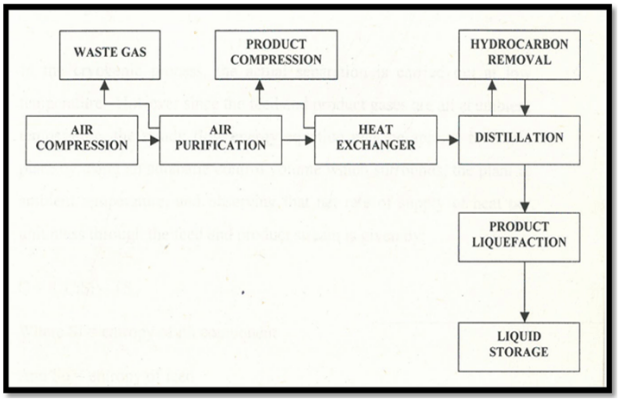

Figure 1: Air liquefaction Process

$$WR = R\,T \sum (C_i \log C_i) \qquad \text{---------- (i)}$$

Where C_i = Molar concentration of ith component

The ideal work is known as minimum work of separation. To find out work of separation per kg Mole of a particular product, WR is divided by molar concentration of the product in the original mixture. In cryogenic process, the actual separation is carried out at low temperature. However since the feed and product gases are all at ambient temperature, the steady flow energy equation may be applied to whole plant by using an adiabatic control volume which surrounds (Figure 2), the plant at ambient temperature and observing that net rate of supply of heat per unit mass through the feed and product stream is given by:

$$Q = T\,CiSi - T\,So$$

Where Si = entropy of the ith component

And So = entropy of feed

These results are identical to equation (i), as it shows the total work required for separating a particular component depend to some extent on how many other gases are produce. For example if it is considered to contain 21% Oxygen, the work required to separate Oxygen only, leaving the other gases mixed is 5555 kJ/Kg mole, while if Oxygen (21%) and Argon (0.934%) are separated, the work to separate Oxygen increases to 6104 kJ/kg mole Oxygen and the work of separation for Argon being 137,000 kJ/kg mole. This also illustrates the marked dependence of the work on initial concentration, which at least partly explains the high cost of the rare gases.

Cryogenic Air Separation process

The Cryogenic air separation process may be considered as a series of unit operations. The various components are closely integrated by the process designer and optimized to suit the particular product requirements and to suit the energy source and cost of compressor operation. It generally works at 6-6.5 bars and sometimes higher. There are some important factors influencing the selections of the process like product quantity, energy consumption, investment cost, product purity, product state, continuity of product supply, plant flexibility, maintenance

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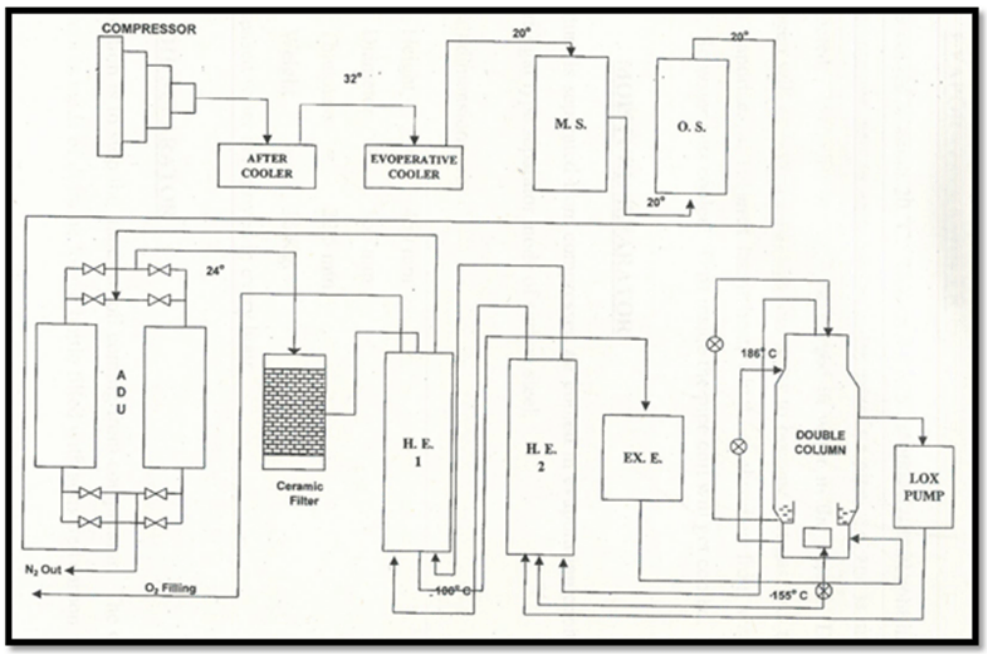

Figure 2: Process Flow Diagram

cost, and permissible plant dimensions. Removal of impurity from feed air is important task [3,7,11].

Water and CO2 must be removed from air feed to prevent blockage of process equipment. Here regenerators and reversing heat exchangers operate during the cooling of air flow while adsorption occurs before the main heat exchanger. For purification of air, removal of moisture and carbon dioxide after compression either molecular sieve + activated alumina drier of reversing heat exchanger or pressure swing adsorption system are adopted. The use of reversing heat exchangers has been gainfully adopted on plants of 1600 cum/hr capacity and above [9].

The visualization of a thermodynamically ideal and reversing system for the separation of gases can be provided some insight into operation and energy requirements of various practical systems. In such system, gases are reversibly separated using factious semi permeable membranes.

Work involved in reversibly separating specified gaseous component of air at 300 K. The ideal work requirement in kJ/kg of Oxygen to reversibly isothermally separate, from air. Air mixture is considered to be consisting of 79.054% Nitrogen, 20.946% Oxygen, by volume at 300 K [8].

Using equation,

$(-W_m/N_m)\ T_m\ E\ Y_i \ln (1/Y_i)$

To separate Oxygen Component from air the work of separation required can be calculated as follows:

$(-W_m/N_m)$ =8.314 X 300 X [0.79540 ln (1/0.79540) + 0.20946 ln (1/0.20946)]

=2494.2 X [0.1820751 + 0.3274325]

=2494.2 X 0.5095076

=1270.8 kJ/Kg

Therefore the work required for separation of unit of mass of Oxygen gas from air will be 1270.8 kJ/Kg.

A series of operations similar to the ideal Linde Hampson System is carried out. Separation of gases is done by Rectification, which is the cascading of several evaporations and condensations, carried out in counter flow. Including the operations guided by Linde double column system, processes are kept to the approximation of Isothermal compression. This is impossible to achieve it in practice but approximately it is kept near to it by following processes:

• Cooling the air during compression by spraying cold water into cylinder.

• Cooling the air during compression by circulating cold water through the cylinder jacket.

• Adopting multi-stage compression with inter stage cooling.

This keeps the compression process near to isothermal process. It is a common practice to provide intercoolers between the cylinders of multistage compressors, for the purpose of cooling the compressed air to atmospheric temperature before entering the succeeding stage.

Equipments

• **Air Compressor:** I.R. compressor having four stages of compression is used. The power requirement to run the compressor when fourth stage is delivering 876.4 PSIG is approx. 95 kWh. Clean, soft ware is used. Maximum water entering the system will be required for satisfactory performance (Table 3) [10,26].

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Table 3: The approximate Air temperature at Suction/Discharge stages

Stage	Suction Temperature °C	Delivery Temperature °C
1	35.0	157
2	43.3	170
3	43.3	163
4	43.3	108

Technical characteristics of air compressor:

Air flow at average conditions = 444 Cu.M/h.

Suction temperature = 35 °C

Suction pressure = 760 mm of Hg

Relative humidity = 75%

• **Air Compressor:**

With pulley and belt guard

H.P = 128.5 BHP (94.3 kW)

Volts = 440

Ampere = 195 max.

• **Air Suction Filter:** Dry type: Woolen pad inserted between mesh.

• **Evaporative Cooler:** Air is cooled to about 20°C. This cooler is an elliptical vessel split into two compartments. In each compartment there is a pipe, coil and is interconnected. The coils are half submerged in water in the vessel. Dry Nitrogen will be bubbled through this water to become wet gas. As the water vaporizes, it requires latent heat and this is absorbed from water itself. So water gets cooled. Thus inside the pipe coil will get cooled.

• **Moisture Separator:** Moisture is separated from compressed air cooled in evaporation cooler. Centrifugal type separator mode of carbon steel.

Overall dimensions are:

Height = 460 mm

Diameter = 165 mm

Thickness = 22.5 mm

Weight = 36 kg

Condensed water is removed in every hour.

• **Oil Separator:** Its function is to stop the traces of oil coming from compressor. The oil separator is made of domine forged bottle filled with activated carbon.

• **Molecular sieve battery:** The dryer battery comprises of two domine forged bottle filled with molecular sieve type 13-X. As the process air passes through the molecular sieve will absorb water vapour and CO_2 from air. The air enters at the bottom in the axis of the bottle and it goes out through the top. The adsorption cycle is 10 hrs.

Type of absorbent – Molecular sieve type 13-X

Quantity of Molecular Sieve – 105 kg per each drier

Flow rate of regenerated gas – 440 cm.m/hr for 10 hrs

Regeneration gas – Dry Nitrogen

• **Regeneration electric heater:** U shaped iron clad resistance. This resistance is solder-raced on the tubular plate in order to secure tightness. There is a thermostat mounted on the inlet air so as to prevent overheating. The electric heater uses 9 kW. When the outlet temperature reaches to 180 °C the molecular sieve is regenerated.

• **Ceramic filter:** The dry air is again filtered in a ceramic filter to avoid any dust entry to cold box.

• **Heat Exchanger - 1**: The compressed air is cooled to about 20 °C and enters the heat exchanger-1 which is a multi-pass coil type heat exchanger. The incoming air is cooled to -100 °C.

• **Heat Exchanger - 2:** The air from heat exchange-1 is bifurcated into two streams. One stream is passed through heat exchanger-2 at 40 kg/sq.m/-100 °C and further cooled to -155 °C by the outgoing Oxygen and Nitrogen.

• **Expansion Engine:** Main stream of air from H.E. 1 is expanded in an Expansion Engine to -15 °C.

Type of Expansion Engine - SEM 0.5/1

No. of Cylinder = 1

Inlet pressure = 60 kg/sq.C.M.

Outlet pressure = 5 kg/sq.C.M.

Throughout volume at 60 kgf/sq C.M. and 8 °C = 300N Cu. m/hr

Throughout volume at 50 kgf/sq C.M. and -75 °C = 120-390 N.Cu m/hr

Power required = 6.5 kW

R.P.M = 200 rpm

• **Expansion Valve:** The air will then expanded by an Expansion valve to form liquid air.

• **Distillation Column:** It is a double rectification column made of three elements. A middle pressure column with 22 trap and coiled vapor is at the bottom of M.P. column, which acts as a re-boiler for the column.

• **Insulating Jacket:** It is made of metal which is closed by removable panels and contains all elements, which are to be insulated distillation column, coiled exchanger, cooler, compression unit of pump etc. The insulating material used is mineral wool and perlite.

• **Lox pump:** This pump is used to compress the liquid oxygen coming out from the fraction column. It is of reciprocating type with its axis vertical, fixed on the rate frame of the insulating jacket with a flange.

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Type of pump = IL/IK/100/22

No. of Cylinders = 1

Power required = 1.5 kW

Normal delivery = 80 N Cu.m/hr

Discharge pressure = 165 kg/sq. C.M.

Suction pressure = 0.5 kg/sq. C.M.

Modifications

Since the conventional plant consumes more power and efficiency is also low, we need to adopt certain modifications in the plant, like: [13,14,15]

• Boosting up of Oxygen plant: By knowing exact quantity of Air feed suitable air compressor can be added into the plant process circuit (Figure 3).

• Calculation for selection of Booster Compressor for Oxygen Plant

Data Available

Free air delivery (FAD) = 440 N Cu. m/hr

Extraction = KY_k/MY_m [1]

Where: K – Flow rate of product 75 Cu. m/hr

M – Flow rate of frf in Cu. m/hr

Y_k- Molar fraction of Oxygen in product = 0.995

Y_m – Molar fraction of Oxygen in feed = 0.21

For present Oxygen plant the maximum capacity of ADU and ASU was mentioned to be 890 Cu. m/hr

For double column air separator producing Oxygen as a product extraction factor is about 0.96-0.97

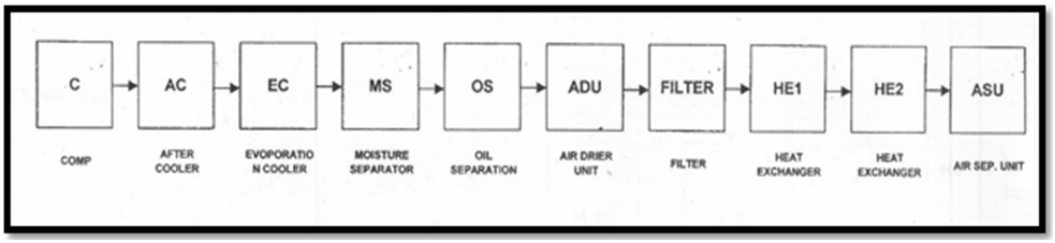

Figure 3: Plant Circuit

Taking the value of extraction factor = 0.96 for our use

With K = 75 Cu. m/hr

M = 440 Cu. m/hr

Y_k = 0.995

Y_m = 0.21

Extraction factor = 0.9 (which is less than specific heat)

For Extraction factor to be 0.96 K will be

0.96 =KY_k/MY_m

K = 89.14 Cu. m/hr

Plant is getting fewer yields because of the poor extraction factor.

Loss = 89.14 – 75 = 14.14 Cu. m/hr

To get additional production of 14.14 Cu. m/hr for the same extraction factor 0.9 the additional

M = (14.14 X 0.995) / (0.9 X 0.21)

= 74.4 N Cu. m/hr

So we need to increase the fee of air by an amount of 74.440 Cu. m/hr. hence compressor of capacity (Table 4) 80 Cu. m/hr will serve the purpose.

Hence the following compressor is used:

Name: SIEMENS

Table 4: List of Equipment

Description	Quantity	Rates Capacity/ kW	Total Capacity kW
Air Compressor	1	128.5/94.3	94.3
Drier heater	1	-	9
Expansion Engine	1	-	7.5
Lox Pump	1	-	2.2
N_2 gas blower	1	-	2.2
Defrost heater	1	-	2.2
Cooling water pump	1	-	2.2 X 2
Chilling plant	2	-	6
Light loads	1	-	1

Through put: 120 N Cu. m/hr

Pressure: 40 Kg/sq. CM

Speed: 300 rpm

No. of cylinders: 2

No. of stages: 3

Theoretical Power = n/n – 1 P1V1 [1-(P2/P1) n/n-1]

Where P1 = 1 Kg/sq. m

T1 = 250 °C

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P2 = 40 Kg/ sq. m

V1 = 120 N Cu. m/hr

n = 1.32 (assumed)

Putting all values, Theoretical Power = 20.5 kW.

The maximum production rate observed by using this booster compressor is 86 Cu. m/hr, while it was expected to be about 90 Cu. m/hr. This reduced production rate is due to lesser FAD to the ASU of the plant (Figure 4) [16-20].

• **Reduction of head pressure:** High-pressure compressor is more powerful per cubic meter of Oxygen produced, as it is difficult to achieve isothermal efficiency and high Air losses. Hence cold production by Freon system, where Freon compressor is used for cooling air by providing Freon exchanger in cold box, which reduces head pressure, should be used. This also controls the inlet temperature of air to molecular sieve batteries to reduce moisture load in air driver unit. So Freon compressor along with Vaporization cooling system is adapted (Table 5).

Table 5: Showing the saving resulting from moving the compressor air intake to cooler one

Temperature of Air Intake	Intake in Cu. m required to deliver 1000 Cu. m of free air at 21 °C	% kW saving or increase relative to 21 °C
-1	925	7.5 saving
5	943	5.7 saving
10	962	3.8 saving
16	981	1.9 saving
21	1000	0
27	1020	1.98 saving
32	1040	3.8 saving
37	1060	5.7 saving
43	1080	7.6 saving
49	1100	9.5 saving

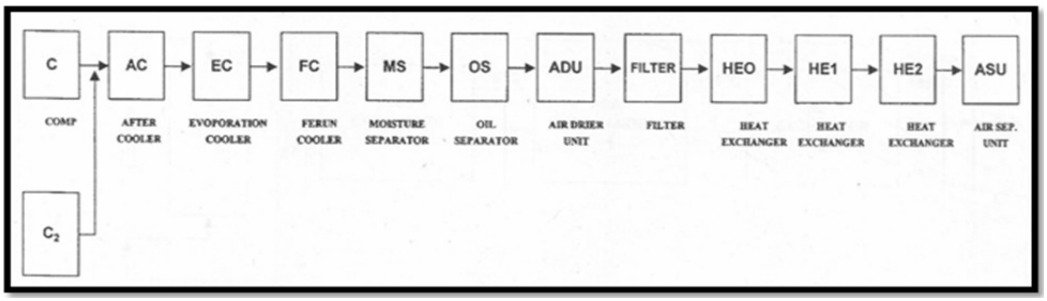

Figure 4: Modified Plant Circuit

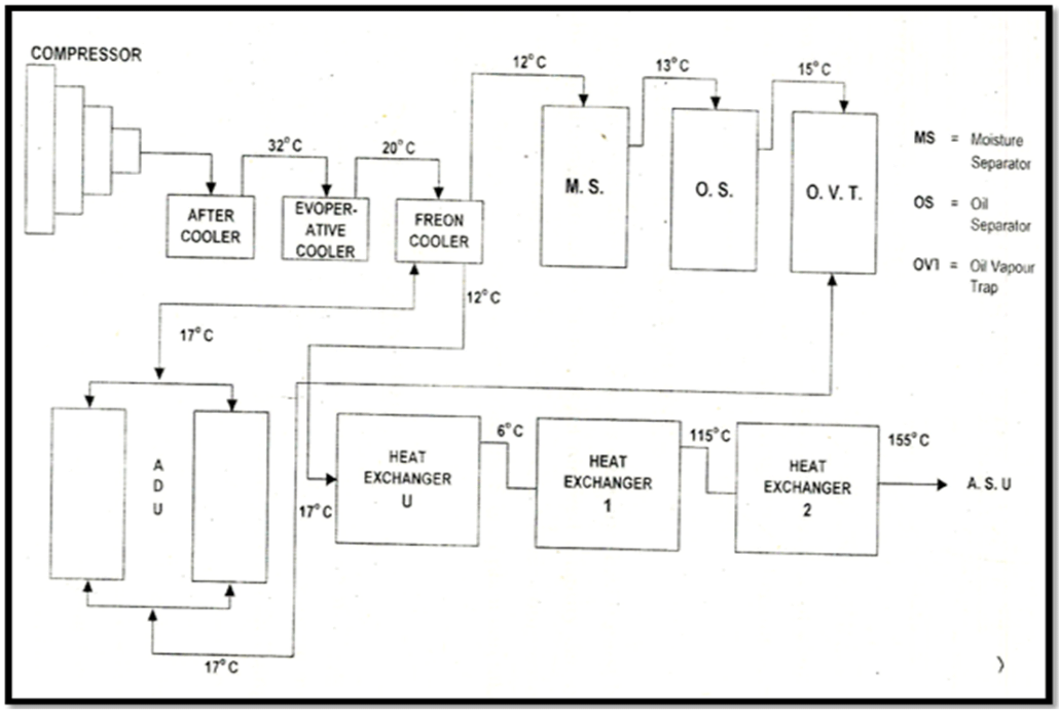

Figure 5: Temperature Recorded in Modified Circuit Line. (Pressure = 49 kgf/cm^2)

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• **New Air purification System:** Activated Alumina Drier is used for moisture and CO_2 removal. The air inlet temperature is reduced from 12°C, which shows lesser moisture in A.D.V. The heating temperature of drier cycle which will cause reduced drier cycle timing and thus power consumption by nitrogen blower and regenerator purification heater (Figure 5).

• **Utilization of Cold:** The quantity of heat transmitted through walls of refrigerator per unit of time is function of 3 factors whose relationship is expressed in following equation:

Q = (A) X (U) X (Tp)

Where, Q - The rate of heat transferred (Watts)

A - The outside surface is of Wall (sq.m)

T_p - The temperature difference across the wall

U Factor depends upon thickness and thermal conductivity of material used in the wall construction. Proper Insulating material to prevent heat intake into cooling system

Table 6: Compressor temperature details

Stage	Pressure Ratio	Suction Temperature °C	Delivery Temperature °C	Compression Index
1	2.245	35	157.22	1.7
2	4.209	43.3	170	1.309
3	3.26	43.3	160.25	1.36
4	1.934	43.3	108	1.38

• **Cooling tower modification:** here use of Induced draft type of cooling tower is used to save water, and ultimately energy for plant.

• **Cooing of intake air:** Solar operated adsorption refrigeration system is used to cool the suction air by providing Heat exchangers.

• **Pre cooling of cooling water:** Water provided at 30-33°C is cooled further, so that compression work is decreased [20,21,22].

Performance Analysis & Results

•Compressor

Compression index: With the help of compression index of each stage one can know the closeness of actual compression process of each stage to isothermal process, where it is unity (Table 6) [4,20,22].

$(P2/P1) = (T2/T1)\ n/(n-1)$ ----------(*)

Where,

P_2= Delivery pressure of each stage

P_1= Suction pressure of each stage

T_2= Delivery temperature of each stage

T_1= Suction temperature of each stage

Stage 1:

$P_2/P_1 = 2.245$

$T_2 = 157.22 + 273 = 430.22$ K

$T_1 = 35 + 273 = 308$ K

From equation (*),

$2.245 = (430.22 / 308)(n/n-1)$

$\log 2.245 = (n/n-1) \log [1.396]$

$n = 1.7020$

Stage 2:

$P_2/P_1 = 4.209$

$T_2 = 170 + 273 = 443$ K

$T_1 = 43.3 + 273 = 316.3$ K

From equation (*),

$4.209 = (443 / 316.3)\ (n/n-1)$

$\log 4.209 = (n/n-1) \log [1.405]$

$n = 1.309$

Stage 3:

$P_2/P_1 = 3.26$

$T_2 = 160.55 + 273 = 433.55$ K

$T_1 = 43.3 + 273 = 316.3$ K

From equation (*),

$3.26 = (433.55 / 316.3)\ (n/n-1)$

$\log 3.26 = (n/n-1) \log [1.370]$

$n = 1.36$

Stage 4:

$P_2/P_1 = 1.934$

$T_2 = 108 + 273 = 381$ K

$T_1 = 43.3 + 273 = 316.3$ K

From equation (*),

$3.26 = (381.54 / 316.3)\ (n/n-1)$

$\log 3.26 = (n/n-1) \log [1.206]$

$n = 1.3$

• **Work Done analysis**

$$W = \frac{n}{n-1} mRT \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \text{ ---------- (**)}$$

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M = 1 kg

N = 1.722

R = 0.287 kJ/kg °C

Stage 1:

From equation (**)

$W = \frac{1.7}{0.7} X\ 1\ X\ 0.28\ X\ 308\ [(2.245^{\frac{0.7}{1.7}}) - 1]$

W = 83.7186 kJ/kg

Stage 2:

$T_1 = 2.73 + 43.3 = 316.3$

$P_2 / P_1 = 4.208$

N = 1.311

From equation (**)

$W = \frac{1.3}{0.3} X\ 1\ X\ 0.287\ X\ 316.3\ [(4.209^{\frac{0.3}{1.3}}) - 1]$

W = 153.846 kJ/kg

Stage 3:

T_1 = 316.3 K (P2 / P1) = 3.26

N = 1.356

From equation (**)

$W = \frac{1.36}{0.36} X\ 1\ X\ 0.287\ X\ 316.3\ [(1.934^{\frac{0.36}{1.36}}) - 1]$

W = 124.467 kJ/kg

Stage 4:

$T_1 = 316.3$

$P_2 / P_1 = 1.934$

N = 1.356

From equation (**)

$W = \frac{1.38}{0.38} X\ 1\ X\ 0.287\ X\ 316.3\ [(1.934^{\frac{0.38}{1.38}}) - 1]$

W = 65.481 kJ/kg

Total work input = 427.513 kJ/kg

It is difficult to bring the temperature of compressor down to 35 °C. In relation to this condition, the actual work input can be compared for analysis of reciprocating compressor.

Stage 1:

$W = \frac{n}{n-1} mRT\ [(\frac{P_2}{P_1}^{\frac{n-1}{n}}) - 1]$

N = 1.3

W_1 = 77.316 kJ/kg °C

Stage 2:

$W_2 = \frac{1.3}{0.3} X\ 1\ X\ 0.287\ X\ 316.3\ [(4.209^{\frac{0.3}{1.3}}) - 1]$

W_2 = 148.203 kJ/kg

Stage 3:

Table 7: Delivery temperature for same pressure ratio (N=1.3)

Stage	Pressure ratio	Suction Temperature °C	Delivery Temperature °C
1	2.778	35	116
2	2.778	43.3	127
3	2.778	43.3	127
4	2.778	43.3	127

$W_3 = \frac{1.3}{0.3} X\ 1\ X\ 0.287\ X\ 316.3\ [(3.26^{\frac{0.3}{1.3}}) - 1]$

W_3 = 118.142 kJ/kg

Stage 4:

$W_4 = \frac{1.3}{0.3} X\ 1\ X\ 0.287\ X\ 316.3\ [(1.924^{\frac{0.3}{1.3}}) - 1]$

W_4 = 61.954 kJ/kg

Total W_{in} = 405.615 kJ/kg

% Saving in Win = [(427.513 – 405.615) / 427.513] X 100

= 5.12 %

• Pressure ratio Analysis

As pressure ratio in all the four stages of compressor are different, but for better performance, pressure ratio in all the stages should be equal (Table 7),

P_1 = 1 atm

P_2 = 60 atm

Pressure ratio of each stage

(60/1)1/4 = 2.778

Hence comparing with the above value, all to be equal

Stage 1:

$P_2 / P_1 = 2.778$

R = 0.287 kJ/kg K

N = 1.3

$P_1 = 308$

$W_1 = \frac{1.3}{0.3} X\ 1\ X\ 0.287\ X\ 308\ [(2.778^{0.23}) - 1]$

=99.83 kJ/kg

$W_2 = W_3 = W_4 = \frac{1.3}{0.3} X\ 1\ X\ 0.287\ X\ 136\ [(2.778^{0.23}) - 1]$

=103.12 kJ/kg

Total W_{in} = 409.189 kJ/kg

% saving in work = 4.29%

• Calculation for Number of stages

$T_2 = 127 + 273 = 400$ K

$T_1 = 35 + 273 = 308$ K

$P_2 / P_1 = (T_2 / T_1)1.3/0.3$

P_2 = 3.103 atm

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Pressure at delivery

P_d = 60 atm

$(P_d / P2) = (T_d / T_2)$ N (1.3/0.3)

(60/ 3.103) = (1.278) N (1.3/0.3)

N = 2.7

So the total no. of stages required are = N + 1 = 3.7 or 4

Heat removed from intercoolers = m C_p $(T_2 - T_1)$

Total heat rejected = Intercoolers-(1+2+3+4)

= (112.896+128.016+118+45.36) kJ/kg

= 404.3 kJ/kg

Heat rejected during Compression process

n = 1.3

C_V = 0.72 kJ / kg

y = 1.4

T_1 = 35 + 273 = 308 K

T_2 = 157 + 273 = 430 K

Stage 1:

$H_1 = C_v \left(\frac{y-n}{n-1} \right) (T_2 - T_1)$

$= 0.72 \left(\frac{1.4-1.3}{1.3-1} \right) (152 - 30)$

= 29.28 kJ/kg

Stage 2:

H_2 = 30.48 kJ/kg

Stage 3:

H_3 = 28.08 kJ/kg

Stage 4:

H_4 = 15.6 kJ/kg

Heat removed during compression = 103.44 kJ/kg

Total heat removed = 103.44 + 404.3 = 507.74 kJ/kg

Conclusion

Mostly in the Cryogenic plant the expenditure is towards energy and raw material (Air), which is available in large amount. Out of this energy, 92-95% goes towards compression of air. The task of decreasing the temperature by solar operated heat exchanger is done.

Analysis part by calculating decrease in power requirement by reducing the intermediate temperature for four stage compressions. In addition to this, Freon cooler is also incorporated before moisture separator, which will increase the performance. Hence if such a system is incorporated it will be beneficial for the industries economically. Hence this is a hypothetical calculation done based upon studies on the oxygen plant design. The findings in the form of values obtained after detailed mathematical calculation is verified by adopting it in cryogenic liquid oxygen plant and this has led to the saving of work up to 4.30%. Hence it is advised to be used in cryogenic plants globally.

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