

Simulation Study of Cryogenic Air Separation Unit Using Aspen Hysys At Rourkela Steel Plant

A thesis submitted in partial fulfilment of the
Requirements for the degree of

Master of Technology
in
Mechanical Engineering
(Cryogenic and Vacuum Technology)

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Abstract

It's been a few days now, requirement of Nitrogen, Oxygen and Argon increases day by day. Especially for a steel industry this three components are very essential for their steel production like decarburization, desulphurization, hydrogen removal, nitrogenation, argon, oxygen removal, metal cutting, welding, and cooling etc. Cryogenic air separation has the best impact to separate the air.

Study and analyses of practical plant performance through computer aided programs has better and cost effective. Aspen Hysys by Aspen Technology is one of the major process simulators that are widely used in cryogenic, chemical and thermodynamic process industries today. In this work, the simulation study of cryogenic air separation unit (Rourkela steel plant, Odisha) is performed by using Aspen Hysys. The simulation study is based on both steady state and dynamic (high pressure column and low pressure column). The dynamic air separation unit has been designed based on PI controller.

The plant efficiency, specific power consumption, product purity and behaviour of process parameter with respect to time and feed disturbance have been discussed.

Key words: Cryogenic air separation unit; cryogenic distillation column; Aspen Hysys; steady state; dynamic; PI control

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Chapter 1

Introduction

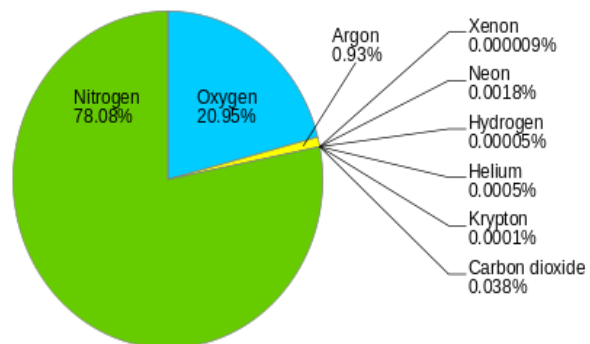


This chapter reports the availability of N₂, O₂ and Ar in the air, uses of these components, types of air separation technique, importance of cryogenic air separation.

1. Introduction

The most important composition of dry air in the atmosphere is listed in the following table: 99.04% of the air is a composition of oxygen and nitrogen and argon 0.93% of air by volume. Whereas the composition of hydrogen, CO₂ and hydrocarbons are vary within certain limits. The moisture content of air differs according to the atmospheric pressure and temperature which is subject to the degree of saturation,

Medium	Chem. Symbol	Volume %	Weight-%
Nitrogen	N ₂	78.1	75.5
Oxygen	O ₂	20.95	23.1
Argon	AR	0,93	1.29
Carbon dioxide	CO ₂	0.033	0.05
Rare gases	---	0.002	---



1.1. Uses of N₂, O₂ and Ar- air separation act as a major role in the current era. The component present in the air (nitrogen, oxygen, argon) has a wide range of

application in several industries like steel industry, chemical industry, semiconductor industry, aeronautical industry, food processing industry, refining and medical industries. Both liquid and gaseous oxygen are used in metals production, welding, clay, glass, clay concrete production, chemicals and petroleum refineries etc. Gaseous nitrogen also used as an inert gas in the steel plant, chemical plant, petroleum plant, material and electronics industries. Liquid nitrogen is used in cryogenic plastic grinding, food preserving. Rare gas argon is used like an inert gas in welding, metal cutting, heat treatment etc. In steel plant and electronic manufacturing process [10].

One example of a pressure driven cryogenic air separation units (ASU) has found application in Rourkela steel plant, which required a high amount of oxygen, nitrogen, argon for their steel production, metal cutting, welding, and cooling. Generally the steel plant uses these gases for decarburization, desulphurization, hydrogen removal, nitrogenation, argon, oxygen removal degassing of steel. For decarburization of 25t of steel it requires 81 nm³/min of oxygen [4].

1.2. Types of separation technique-mainly there are three type of air separation techniques are used that are (a) distillation,(b) adsorption and(c) membranes [11]. Distillation technique is the most efficient of the three technologies. And able to produce for both high purities greater than (99%) and large scale productions [12]. Adsorption technology able to produce purities of oxygen up to 95% but this technique require adsorbent which has limits its size and saturation problem and also costly capacity due primarily to capital costs [5][13].

Other methods of air separation techniques are pressure swing adsorption and Vacuum Pressure Swing Adsorption, are used to separate a single component from atmospheric air. But high purity oxygen, nitrogen, and argon are produced by cryogenic distillation.

1.3. Importance of cryogenic air separation: Cryogenic air separation technology has the ability to produce the largest capacities of products at a moderate to high-purity level, compared to non-cryogenic based systems such as pressure-swing adsorption and membrane technologies, which are employed at the lower end of production scale and low purities [9].

The ability of the process operation of the air separation unit can be improved by automation and advance control of the plant. Advanced control has been used in the air separation from the last decades. The first application of computer aided control system for an air separation unit was used in the early 1970s. Since that time the advance control technique has been used to improve purity, productive and efficiency of the air separation plant [10].

Chapter 2

Literature review

This chapter reports the literature review and available research work on Cryogenic air separation.

Vinson et al. suggested that to achieve high performance process control (HPPC) required advance control system. He also presented HPPC challenges for both adsorption and cryogenic air separation. He also presented the practical challenges of air separation process, because of their nature of energy consumption and demand of the product. They also demonstrated about advance controller and model predictive controller [10].

Mahapatra et al. designed and studied a pressure driven cryogenic air separation unit for IGCC Power Plants. In his study he designed the air separation unit (ASU) based on model predictive controller (MPC) by Aspen Plus and Aspen Dynamic to understand the performance of model predictive controller (MPC). He also interfaces with Matlab and Simulink. They also suggested/ proposed A PID-based controller to maximize or optimize the dynamic plant [2].

Stephen et al. explain dynamic maximization of oxygen yield of an elevated pressure driven air separation plant using model predictive controller (MPC). They found that, the flow rate of the liquid nitrogen stream connecting from the high-pressure to low-pressure column has a major impact on the total oxygen yield. They also proposed a model predictive controller for the dynamic plant under load change and process disturbance [9].

Sapali et al. simulate a medium purity cryogenic air separation plant with a bio mass gasifier in Aspen Plus. They found the purity of Oxygen 96.2% with a specific power consumption of 0.2435kW/scmh of O₂. They also observed that major exergy loss taking place at cold box (main heat exchanger), distillation column, and compressor [14].

Thomas et al. pointed out that oxy-fuel combustion process requires oxygen separation from the air on a large scale. This separation is done through cryogenic distillation process. They also examined that hybrid membrane and cryogenic separation is better suitable. They also found that using a vacuum pump arrangement to draw the air through the membrane has a high impact on energy consumption on the plant. They also found that this hybrid system is more suitable and productive from small scale to medium scale application. [13]

Ruhul et al. Simulate the N₂ gas separation from air via Linde- Hampson cycle using Aspen Hysys. And they found the nitrogen purity of 91.75% [15].

Shoujun et ai. Modeled the high purity dynamic air separation column by compartmentally using Aspen Technology and nonlinear model predictive control for upper column [16].

Manenti et al. Suggested the possibility of further intensify of air separation units. Their modifications of the conventional process layout are proposed and simulated by means of simulation suites. They suggested the modifications with the upgrading of recycle of rich argon stream, oxygen purity, and the possibility to generate energy. They also compare the novel process with the traditional process [24].


Huang et al. Proposed that the nonlinear model predictive control (NMPC) is very essential for high performance of dynamic air separation plant. Because of the fluctuating operating conditions to respond to changing product demands. With him work, they make use of advanced step NMPC controller to overcome these limitations. They also demonstrate that the controller can handle nonlinear dynamics over a wide range of operating conditions [25].

Heong et al. Presents an overview of tuning and functionalities methods in software packages, patents and commercial hardware modules. They have seen that many PID variants have been developed in order to improve transient performance, but modularising and standardising PID control are challenging. The inclusion of system identification and “intelligent” techniques in software based PID systems helps automate the entire design and tuning to a useful degree. This should also assist future development of “plug-and-play” PID controllers that are widely applicable and can be set up easily and operate optimally for enhanced productivity

Liwei Yan et al. simulated a large-scale air separation unit based on the industrial operational parameter and process of a petrochemical company using ASPEN PLUS. They analyse actual performance for the total site. According to the simulation results, they analyse exergy efficiency of major equipment. They solve a optimization problem by a new algorithm, which combines genetic algorithm with linear programming. Accordingly a modified air separation process is proposed. The equipment deficiency is overcome in the new process. Also the structure packing column and nitrogen expansion are added. They also analysis the pinch analysis for the new process. The results of the pinch analysis considering the impact of phase transition agree better with industrial data than those without doing so. The energy consumption can be 7.55MW lower than the original process. The total energy efficiency can be raised by 27.21%. Finally seven unified principles for energy saving, which can be widely used in air separation process, they summarized [27].

Chapter 3

Process concept & Process description



This chapter explain the process concept of air separation technique, process description of Rourkela steel plant and factor influencing distillation process.

3.1. Process concept

Air has a composition of nitrogen 78.08%, oxygen 20.95%, argon 0.93% and their boiling points temperature at atmospheric pressure are -195.79°C (77.36k), -183°C (90.15K), -185.84°C (87.302k) respectively and they are nonreactive .so they can be separated according to their boiling points temperature .the gas mixture which has widely boiling point difference can be separated effectively, but it is less effective for substance which has closer boiling points. Oxygen and argon has closer boiling points also argon has less percentage in the air so it is less effective.

Air can be separated by rectification column with repeated evaporation and condensations in counter flow. So that the light component (vapour i.e. low boiling points component) flows upward in the column through liquid, while the heavy component (liquid i.e. high boiling points component) flows down ward across the vapour stream.

When the vapour flows through the liquid layer, the vapour which has higher temperature transfer heat to the liquid, results condensation of a little bit of higher boiling point component in the vapour and evaporation of a little bit of lower boiling point component from the liquid region. Therefore the vapour moves upward through the liquid gets richer in low boiling component, and the liquid which moves downward gets rich in heavy component i.e. high boiling component. Thus the top of the column is reach in light component and bottom of the column reach in heavy component.

3.1.1. Double-column system

All chemical distillation column are condensing by cooling tower or water, but how to condense these atmospheric gases which has boiling point very low?

This problem was solved by Linde double column system shown In Fig. 3.1. Two rectification columns are attached on top of the other, thus its name double column system. The bottom column is operated at a pressure of 500 kPa to 600 kPa (5 atm to 6 atm), and the top column is operated at a pressure of approximately 100 kPa(1 atm). At 5 atm, the boiling point of nitrogen is 94.2 K which is higher than the boiling point of oxygen at 1 atm i.e. 90.2 K. Therefore, the top of the bottom column get condensation by bottom of the top column component (oxygen), at the same time bottom of the top column get boil by top of the bottom column component (nitrogen).i.e. boiler of the upper column and condenser of the lower

column are coupled by heat exchanger. And some of liquid nitrogen produced by the lower column feed to the upper column for reflux [1].

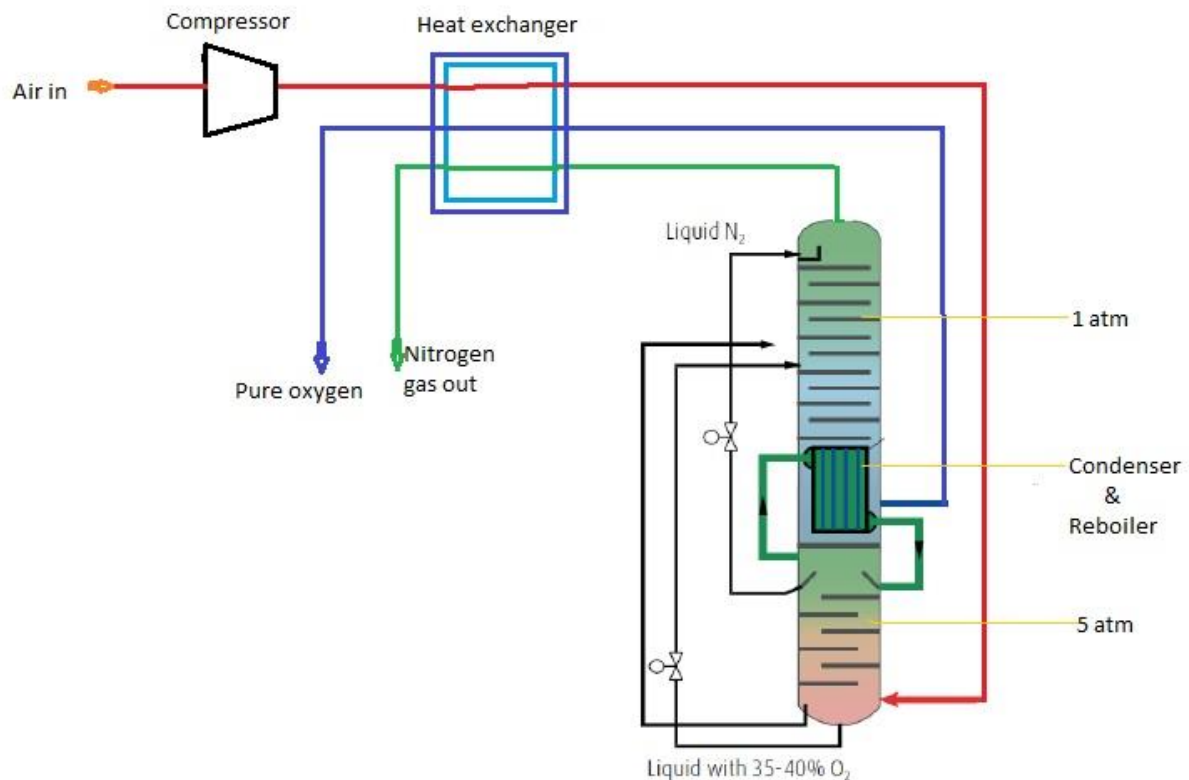


Fig.3.1. Linde double column system

3.2. Process description

The cryogenic air separation technology [17][18][8][19]. Requires a very tight optimization of distillation columns, compressor and heat exchangers [20] to produce high purity of component and a good plant recovery or efficiency with a minimum specific power input in the compressor because all the energy for separation is provided by the main compression of the inlet air of the plant. The size of the operation and the required purity of Oxygen determine the method of separation [5].

3.2.1. Production of oxygen and nitrogen by double column

Process air is filtered by a filter system and compressed to a pressure of 5 to 6 bar in main air compressor (Fig.3.2.). Then the air is cooled in air pre-cooling system i.e. Pre cooler which is cooled by outgoing plant west nitrogen. This pre-cooled air is passed through absorber to

remove all the traces of moisture and CO₂. Generally there are two absorber parallel connected in the line which are working alternately for 4 hours to avoid saturation. After saturation it is regenerated by passing warm nitrogen. This air is split into two parts; one part goes to the Main Exchanger. The other part passes through the Booster Exchanger and this is again divided into two parts, one part enters Booster Compressor where it is compressed to 64 bars in six stages. The Booster Compressor also has got an anti-surge control valve. Booster is also equipped with Inter-Cooler between the stages and an After-Cooler after the delivery. Booster is also equipped with a moisture analyser in the outlet. This is a protection against any water entering into Main Exchanger in case of water leakage in Inter-Cooler and After-Cooler. The other part of the air enters Turbine Booster Compressor. In the inlet of the Booster, there is one Strainer. Air enters the Booster through the strainer and after compression, air leaves at 7.35 bar and proceeds to the Booster Exchanger. For the Booster Heat Exchanger three streams are there- one is cold Stream i.e. From absorber. All these three streams of air i.e. Approx. 5.4 bar air from absorber, air from Booster compressor at 64 bar and air from Turbine Booster at 7.35 bar enters the Main heat exchanger. All these three streams of air are cooled against the returning stream from the column of liquid Oxygen, Nitrogen, waste Nitrogen and Nitrogen seal gas. The air from Turbine Booster is entering the main heat exchanger and withdrawn from the midpoint of main heat exchanger. This air is now sent to the inlet of the Turbine Expander. This expanded air is then fed to the upper column i.e. Low pressure column. The other air stream from the Booster Compressor enters the Main heat Exchanger and then fed to the lower column through a JT valve. The direct air coming from absorber enters Main heat Exchanger and then enter bottom of high pressure column (lower column) for the purpose of boiling.

Nitrogen rich and oxygen rich products from the high pressure column is feed to the low pressure column at top and middle respectively through sub cooler and JT valves for the purpose of reflux. The sub cooler is cooled by outgoing gaseous nitrogen from the top of the upper column. The product of gaseous nitrogen, liquid oxygen, gaseous oxygen, waste nitrogen flows through the main heat exchanger for the purpose of pre cooling the inward flow stream.

A stream from the bottom of the high pressure column having oxygen composition 37% to 40% is sub cooled in the sub cooler then feed to the reboiler heat exchanger to the pure argon column for the purpose of reboiling the pure argon column. Again it expand through a JT valve

then feed to the condenser of the both pure argon and crud argon column, finally sent back to the low pressure column(upper column).

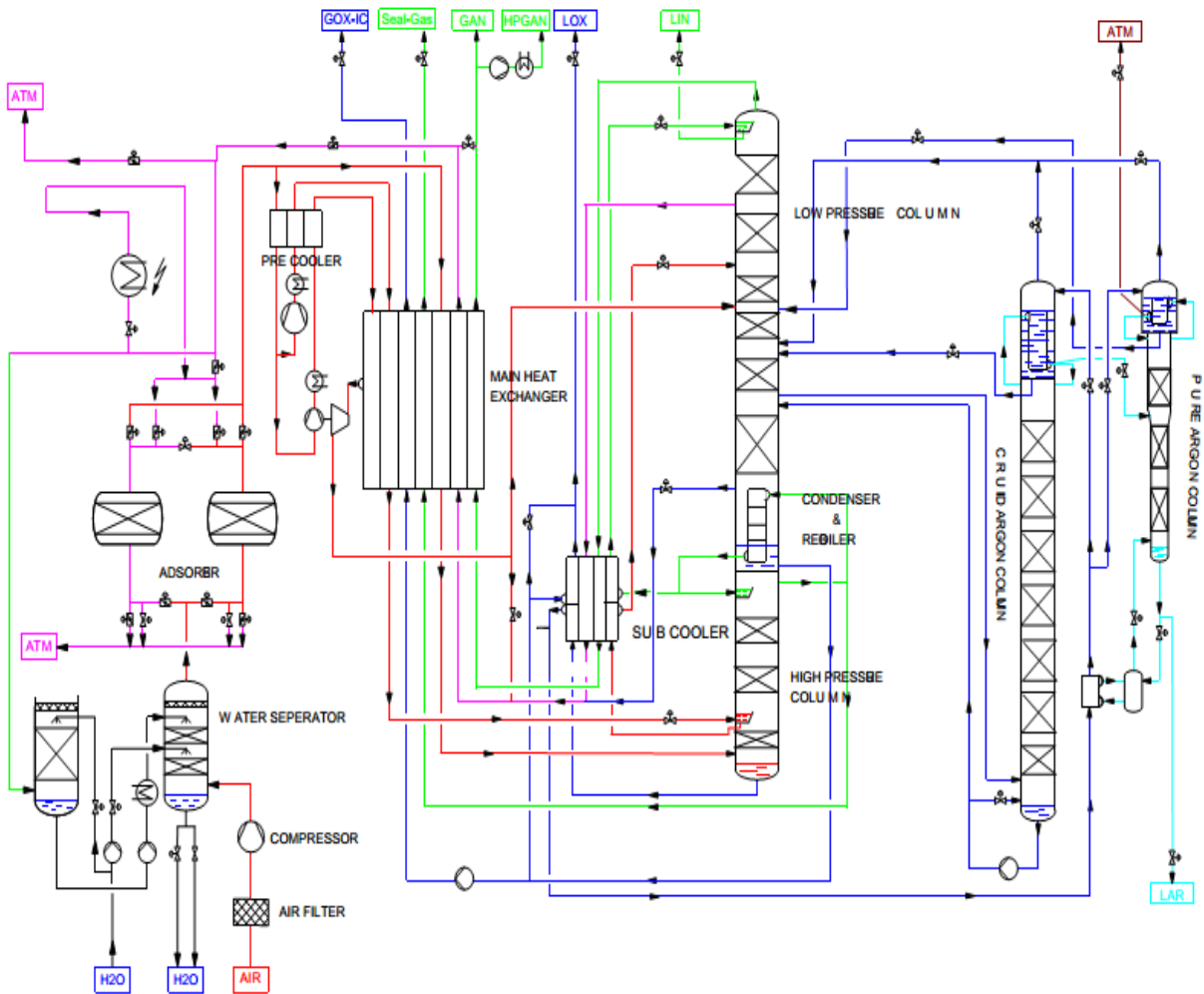


Fig. 3.2. Line diagram of the actual cryogenic air separation (N₂,O₂, AR) plant.

3.2.2. Production of pure argon

Impure gaseous Oxygen i.e. Argon rich Oxygen mixture will be drawn from the low pressure column. The impure gaseous Oxygen is then fed to the crude Argon column. The column consists of a distillation column with crude Argon condenser. The pressure in the condenser is controlled by a valve which is linked to the flow of the impure Oxygen mixture into the crude Argon column. In this column Oxygen is almost completely removed and pure Argon with Nitrogen as impurity is obtained from the top. Argon rich liquid oxygen is withdrawn from the bottom of this column. These are fed to pure Argon column. The crude Argon i.e. Argon and Nitrogen mixture is fed to the pure Argon column by a-controller through a valve and is fed to the column pure argon column. In this column Nitrogen is stripped of Crude Argon and is vented off at the top of the column. Pure Argon is withdrawn from the bottom of the pure argon column and sent to the LAR tanks for storage and consumption. Gaseous argon is supplied to steel melting shop by vaporizing liquid argon in atmospheric vaporizers.

3.3. Factors influencing distillation process

The main factors which influence the distillation process and which can potentially be changed by the operator are the following:

- Product rate
As the withdrawal of any product stream is increased then the purity of that stream decrease. Conversely, reducing the gaseous withdrawal increases the oxygen purity.
- Column loading
For the column to perform adequately, good contact must be maintained between the liquid and vapour on reach tray or section of packing. At low loads there will be insufficient liquid on the trays or liquid will pass through the tray perforations (weeping). At too high a load the space between the trays will become full of liquid (flooding or priming). In either case the separation efficiency will be reduced or even stopped altogether. Packed columns are less sensitive to lower flow rates but liquid distribution may become a problem.
- Reflux ratio
The reflux ratio is the ratio of the liquid flow coming down the column to the vapour flow going up. As with the overall loading there is a minimum and a maximum but

within these limits an increased reflux ratio results in better separation. The reflux ratio of the column may be increased by decreasing the product liquid flow.

- Feed conditions

The feed conditions must be correct. If the feed composition is not at or near design condition then the column will not perform as per design. In addition if the temperature of the feed (for a given pressure) is not correct or if the liquid /vapour ratio of the feed is not as design, the column performance will also be affected.

- Operating pressure

In general a lower operating pressure means easier separation. So if a column is operated at an elevated pressure its performance will be reduced.

Chapter 4

Computational details



This chapter describes the simulation of cryogenic air separation plant (Rourkela steel plant) using Aspen Hysys software both steady state and dynamic and also PI controller.

4.1. Steady state separation plant air

The air separation unit at Rourkela steel plant is simulated by a software aspen hysys (fig. 4.1.). The result obtained quiet similar to the practical data. In this enter simulation we taken Peng-Robinson thermodynamic fluid package and components as nitrogen, oxygen, argon.

Generally the steady state and dynamic air separation plants are designed according to the pressure difference and mass flow rate [2]. The steady-state cryogenic air separation plant which is simulated by aspen hysys (aspen one) software shows the major equipment in figure 4.1. Here absorber and air filters are not shown and assuming the air composition of nitrogen 78.12%, oxygen 20.95%, argon 0.93%. Heat duties of the reboiler of the low pressure column and heat duties of the condenser of the high pressure column are same so they are joined to each other and act as a condenser-reboiler. So there is no extra source of external heat required. Power produced by the turbine is used to run the LP compressor. Both crude argon column and pure argon column are condensed by a stream drawn from the bottom of the high pressure column which has an oxygen composition of 37%. Also a recycler is used to recycle the impure oxygen from the crude argon column. Almost pure argon is produced in the crude argon column but it sent to pure argon column to liquefy as well as removing the unwanted nitrogen.

Table 4.1. Shows the input Simulation parameters for the cryogenic air separation unit,

Table 4.1. The Simulation parameters for the cryogenic air separation unit.

Parameters	Quantity
HP column pressure	535kpa to 549kpa
LP column pressure	133kpa to 140kpa
Crude argon column pressure	123kpa to 138kpa
Pure argon column pressure	115kpa to 120kpa
No. of stage in HP column	62
No. of stage in LP column	80
No. of stage in crude argon column	175
No. stage in pure argon column	50
In put air temperature	28.79°C
Input air pressure	101.3kPa
Input air molar flow rate	4521kgmole/h
Input air composition	Nitrogen 78.12%, oxygen 20.95%, argon 0.93%.

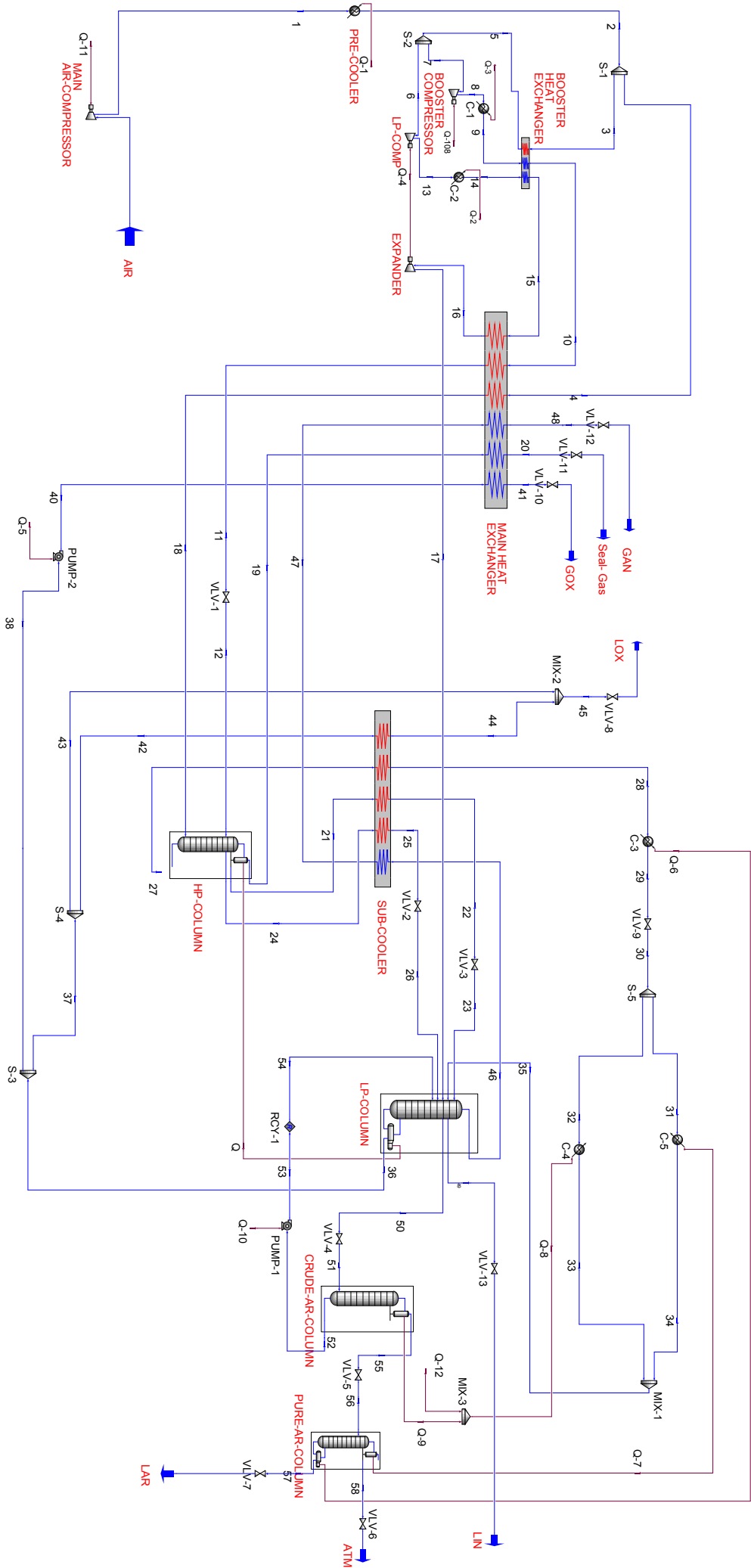


Fig. 4.1. Steady state process flow diagram of air separation plant in aspen hysys.

4.2. Dynamic simulation and control of high pressure and low pressure column

After simulating the steady state air separation unit, we size the vessel and resistance devices and install some PI controller then click in to dynamic mode to study and analyze the process parameter. Here we are only control and analyze the high pressure column and low pressure column (i.e. Only oxygen and nitrogen) due to limited data. The inputs to the high pressure column get cooled by the outgoing stream (LOX, GAN and Seal gas) via main HX(not shown). The dynamic simulation and controller of high pressure column and low pressure column by Aspen Hysys are shown in fig. 4.2.

4.2.1. PID controller

In this simulation we use PID controller [21]. The output of controller is given by

$$u(t) = K_C \epsilon + \frac{K_C}{T_i} \int_0^t \epsilon dt + T_d \frac{d\epsilon}{dt}$$

ϵ =error=SP-PV (SP: Set point, PV: Process variable)

K_C =proportion constant

T_i =integral constant

T_d =derivative constant

Here we are using PI controller

The PID controller controls following parameter

(a) Flow controller: It controls the molar flow in the plant. In fig. 4.2. FIC-101 and FIC-102 are flow controllers, which controls the molar feed in to the high pressure column via valve VLV-100, VLV-107.

(b) Liquid level controller: It controls the liquid percentage level in the vessel. LIC-101 controls the liquid percentage level of condenser of HP column via VLV-3. And controller LIC-102 control the heat supply (Q-100) according to the liquid level in the boiler of the LP column.

(c) Temperature controller: It controls the temperature of the stage 105 which has high variation of temperature via VLV-105.

(d) Pressure controller: It controls the pressure via valves. Controller PIC-102 controls the pressure of the HP column via VLV-101 and PIC-201 controls pressure of the LP column via VLV-108.

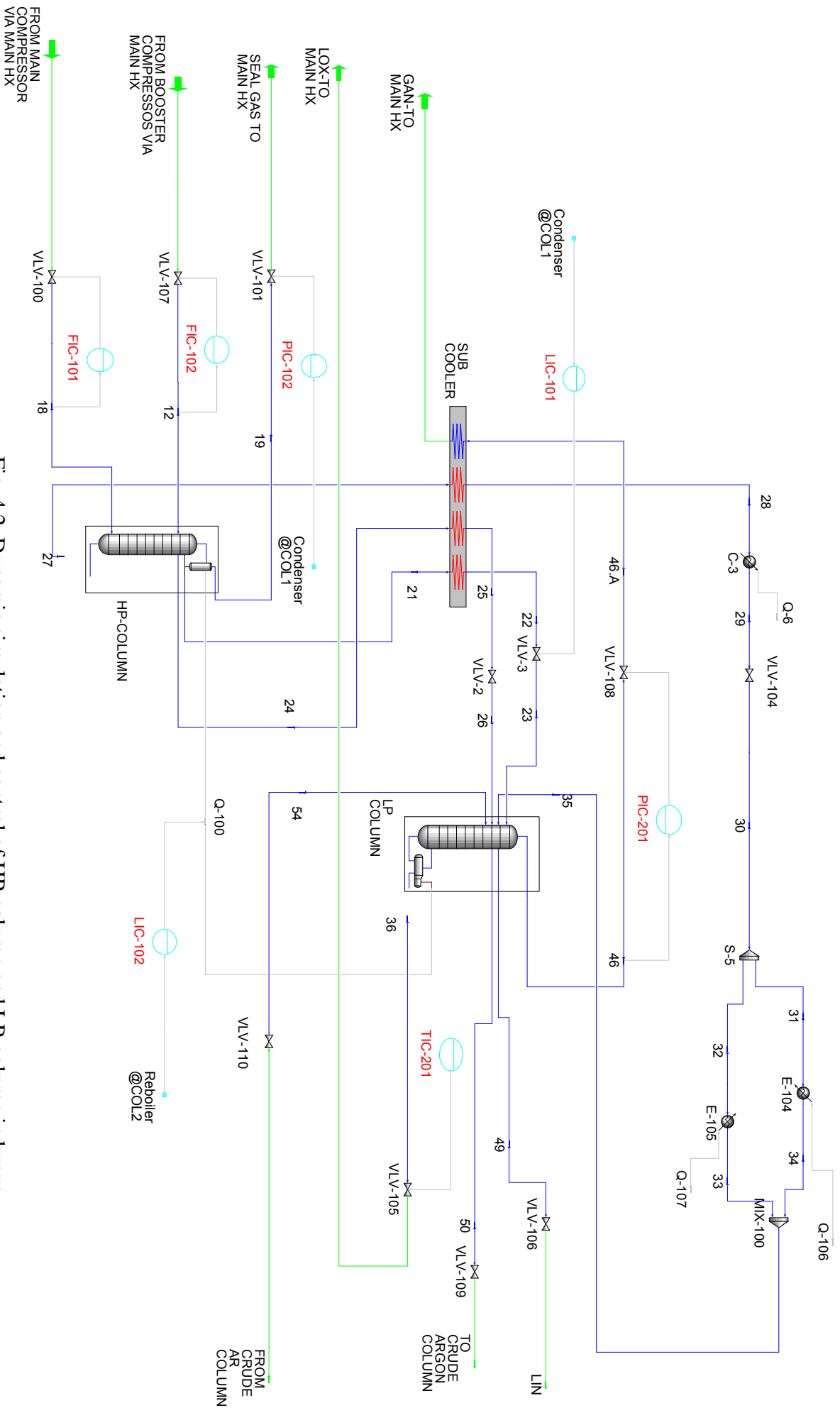


Fig. 4.2. Dynamic simulation and control of HP-column and LP-column in hysys

PV- process variable which has to control

OP- controller out put

SP- set point

Table 4.2. Controller parameters

Controller	PV	OP	Operation parameter	K_C	T_i	PV minimum	PV maximum	SP
FIC-101	Molar flow@18	VLV-100	Reverse	0.1	0.5	0	4952 kg mole/h	2476kgmole/h
FIC-102	Molar flow@12	VLV-107	Reverse	0.1	0.1	0	2610kgmole/h	1305kgmole/h
PIC-102	Vapour pressure of condenser@HP column	VLV-101	Direct	20	1	530kpa	560kpa	535kpa
PIC-201	Pressure@46	VLV-108	Direct	0.1	0.1	130kpa	145kpa	133kpa
LIC-101	Condenser liquid % level@HP column	VLV-3	Direct	2	5	0%	100%	50%
LIC-102	Vessel liquid % level Reboiler @LP column	Q-100	Direct	3	1	0%	100	0.85%
TIC-201	105 Stage Temp. @LP-column	VLV-105	Direct	1	60	-190 ^o	-170 ^o C	-181 ^o C

Chapter 5

Results and discussion

This chapter summarizes all the computational result and analysis in both steady state and dynamic simulation.

5. Result and discussions

5.1. Steady-state simulation analysis

Fig.2.1. (above chapter) shows the simulation of the Rourkela steel plant (RSP) in **Aspen Hysys** for a certain input data. And table 5.1, 5.2 and 5.3 shows the material, energy and composition of all material and energy stream in aspen hysys.

5.1.1. High pressure column

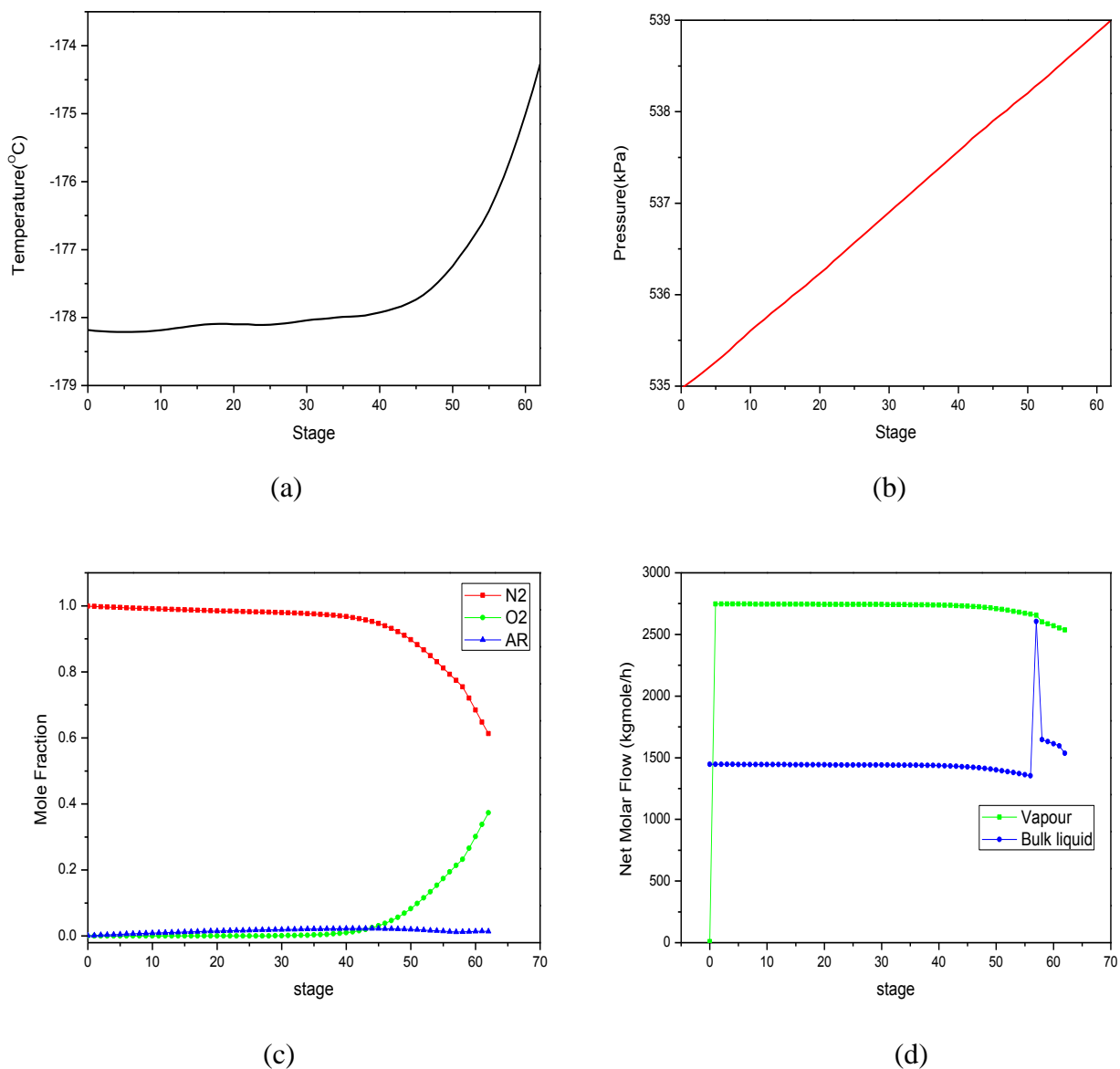


Fig.5.1. High pressure column profile: (a) variation of temperature with stage from top to bottom; (b) variation of pressure with stage; (c) variation of composition with stage; (d) variation of net molar flow with stage.

(a) Temperature profile

Fig.5.1. (a) Shows that temperature of the high pressure column reduces from bottom to top of the column and it maintain a temperature of -174.2°C at the bottom and -178.2°C at the top of the column. The temperature of the high pressure column slowly increases up to 40 no. Stage and after that temperature increase rapidly from stage 40 to 60 due to boiling effect by the stream 18 at the bottom.

(b) Pressure profile

Fig.5.1. (b) shows that pressure variation across the column. The pressure increase from top of the column to bottom of the column linearly. And the pressure at the top stage of the column is 535kpa and bottom stage is 539kpa.

(c) Composition profile

Fig.5.3. (c) shows that composition variation of the high pressure column from top stage to bottom stage. And it observed that nitrogen mole fraction increases from bottom to top of the column whereas oxygen mole fraction increases from top to bottom the column. And argon remains in between them but closer to oxygen. The top of the column reach in nitrogen and has a mole fraction of $\text{N}_2=0.999464$, $\text{O}_2=0.0$, and $\text{AR}=0.000536$. And bottom of the column has a mole fraction of $\text{N}_2=0.612821$, $\text{O}_2=0.372952$ and $\text{AR}=0.014226$.

(d) Molar flow profile

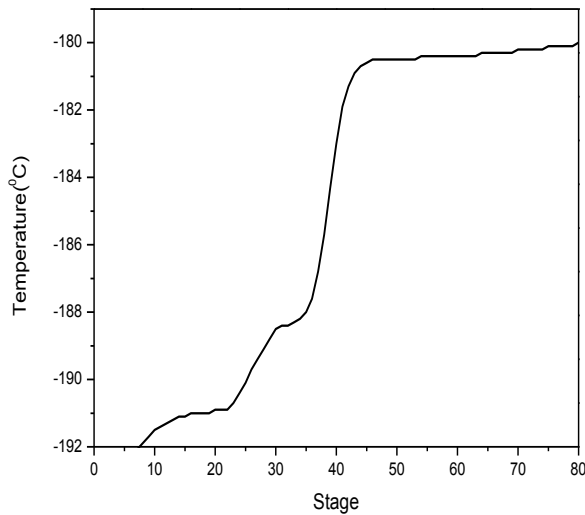
Fig.5.1 (d) shows that vapour and liquid molar flow across each of the stage throughout the column.

5.1.2. Low pressure column**(a) Temperature profile**

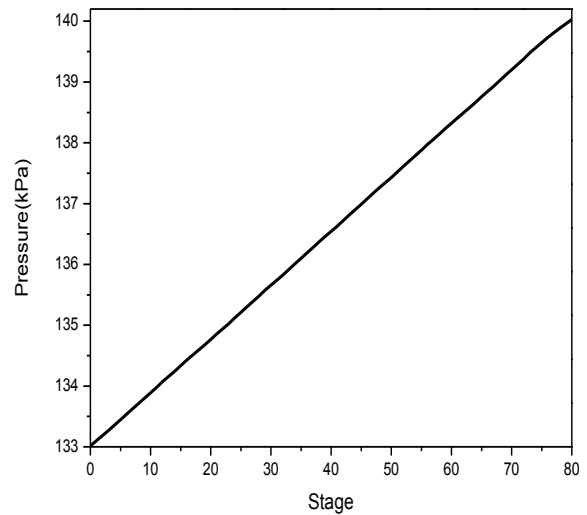
Fig.5.2. (a) Shows that temperature of the high pressure column reduces from bottom to top as -180°C to -193.2°C . From stage no. 35 to 45 There is a high gradient of temperature difference. In dynamic mode it should be controlled with in a certain limit to stabilize the plant.

(b) Pressure profile

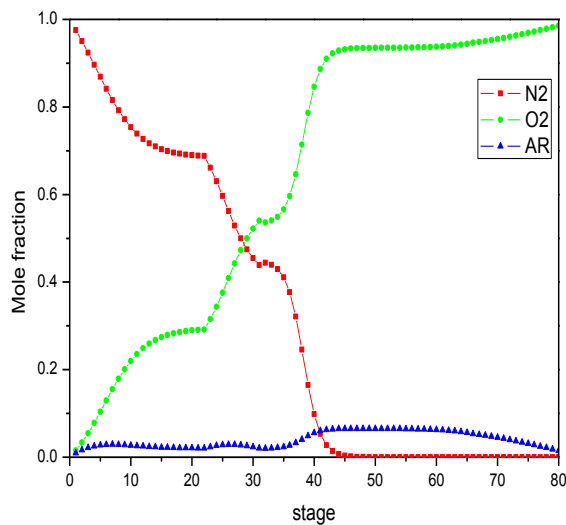
Fig.5.2. (b) shows that pressure variation across the column linearly. And has a pressure of 133kPa and 140kPa at top and bottom respectively.



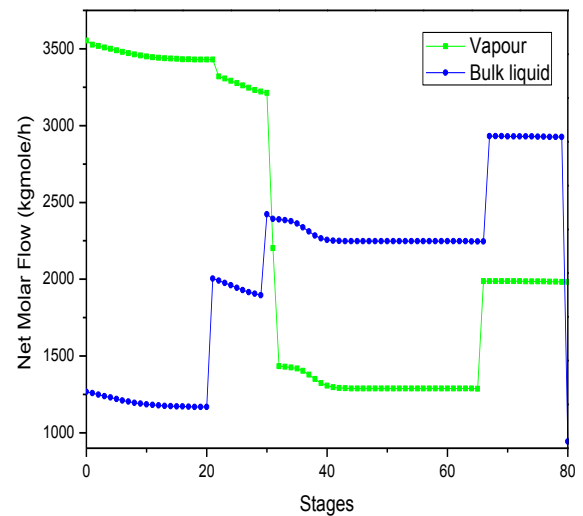
(a)



(b)



(c)



(d)

Fig.5.2. Low pressure column profile from top to bottom: (a) temperature versus stage; (b) pressure versus stage; (c) molar fraction versus stage; (d) net molar flow versus stage.

(c) Composition profile

Fig.5.2. (c) shows that component mole fraction (N_2 , O_2 , and AR) variation across the stage of low pressure column. As compare to the high pressure column it has well separation of both oxygen (0.988886) and nitrogen (0.991531) at bottom and top of the column respectively. Whereas in high pressure column only nitrogen separation (i.e. 0.999464) at the top of the column no oxygen purity. Argon has a high concentration at stage no.66 with zero nitrogen concentration has been drawn and sent to the crude argon column for argon separation.

(d) Molar flow profile

Fig.5.2 (d) shows that vapour and liquid molar flow across the stage throughout the column.at top of the column high vapour flow and at the bottom of the column high liquid flow.

5.1.3. Crude argon column

Fig.5.3. (a), (b), shows that variation of temperature, pressure with respect to stage of the crude argon column. At the top stage the temperature and pressure are -193.2°C and 133kPa and at the bottom stage the temperature and pressure are -180°C and 140kPa respectively.

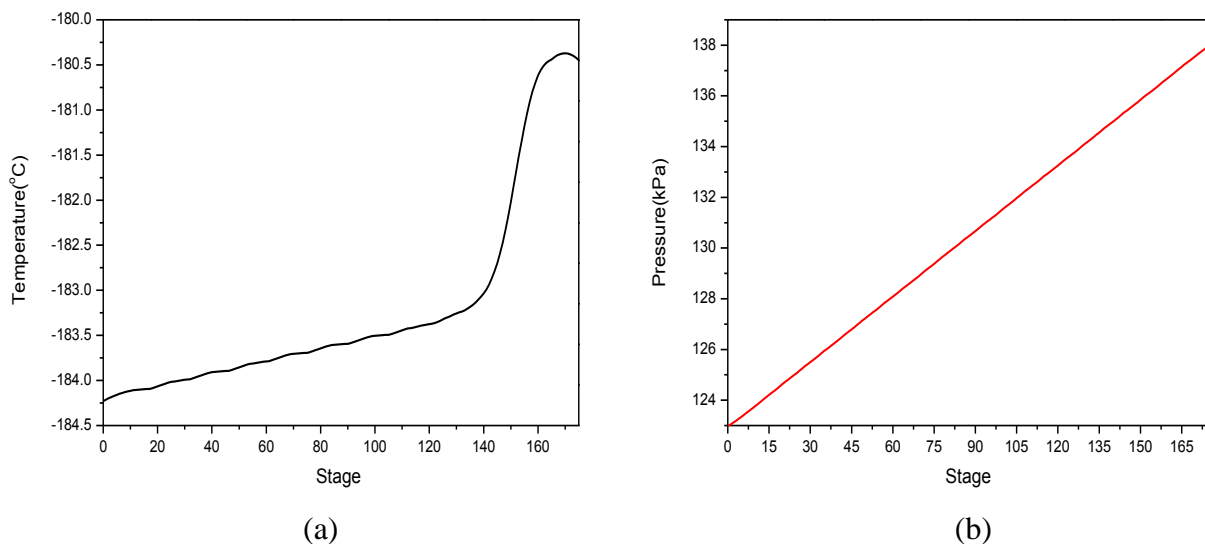
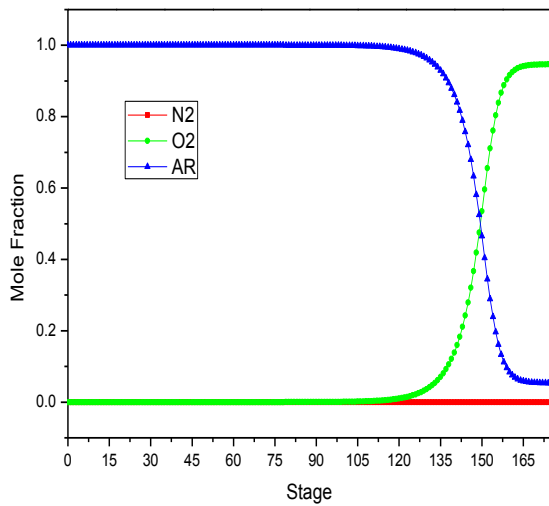
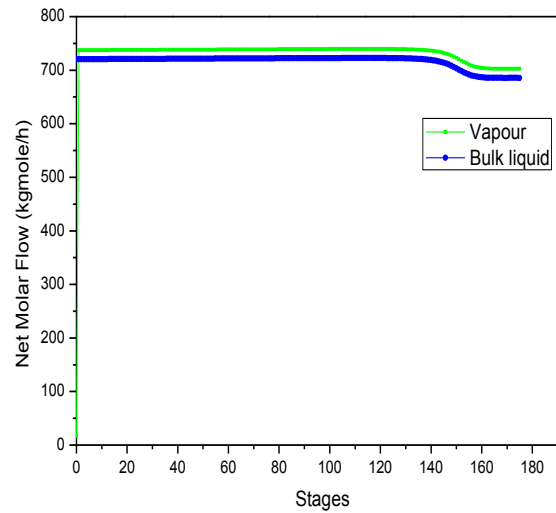


Fig.5.3. Crude argon column profile from top to bottom: (a) temperature versus stage; (b) pressure versus stage

From fig.5.4.(a) and (b) shows the molar fraction and molar flow versus stage position. Almost pure argon is produced at the top of the column and at the bottom of the column impure oxygen is produced which is recycled or sent back to the low pressure column.



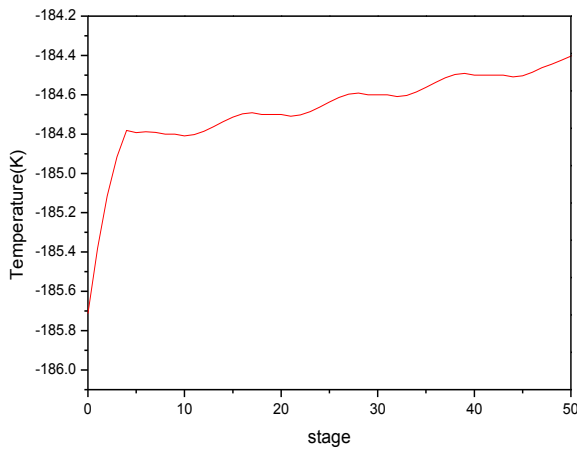
(a)



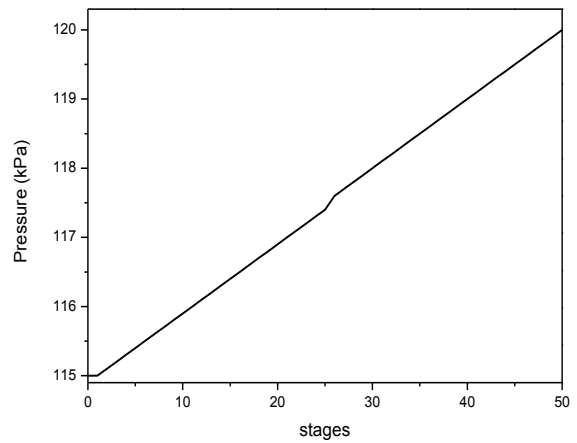
(b)

Fig.5.4. Crude argon column profile from top to bottom: (a) molar fraction versus stage; (b) net molar flow versus stage.

5.1.4. Pure argon column



(a)



(b)

Fig.5.5. Pure argon column profile from top to bottom: (a) temperature versus stage; (b) pressure versus stage

Fig.5.5. (a) And (b) shows the temperature and pressure versus stage position of the pure argon column. At the top of the column it maintains a temperature and pressure of -180°C and 123kPa respectively. And at the bottom of the column it maintains a temperature and pressure of -184.4°C and 120kPa respectively.

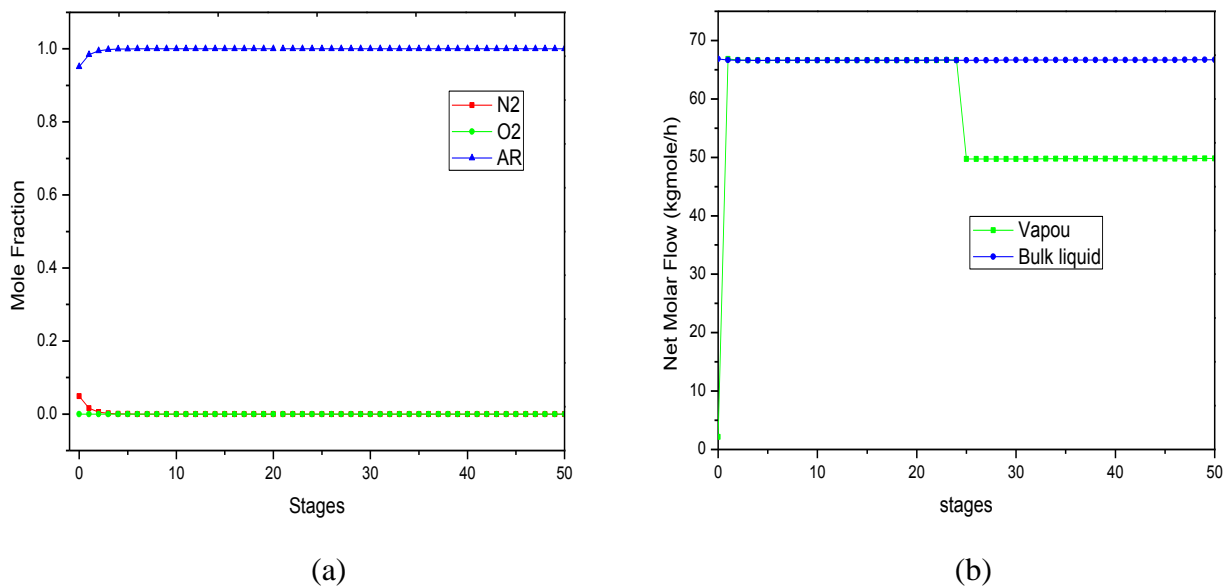


Fig.5.6. Pure argon column profile from top to bottom: (a) molar fraction versus stage; (b) net molar flow versus stage.

Fig.5.6 (a) and (b) shows the molar fraction and molar flow through the stage of the column respectively. At the top of the column a tiny amount of nitrogen is present which is vented out to the atmosphere and at the bottom of the column pure argon is present.

5.1.4. Heat exchanger

The energy transfer between the two streams (cold and hot) can only be possible if the temperature difference between them is above a certain minimum value. The ΔT_{\min} between the two streams at which heat transfer is possible is called pinch point. This ΔT_{\min} is the minimum driving force of heat transfer. If ΔT_{\min} increases it has a high driving force of heat transfer and it requires less heat exchanger area hence less cost [23][22].

Fig.5.7. (a) and (b) shows the temperature versus heat flow and overall heat transfer of hot and cold composite of Main heat exchanger. The minimum vertical distance between hot and cold composite in the temperature versus heat flow graph is called pinch point [22]

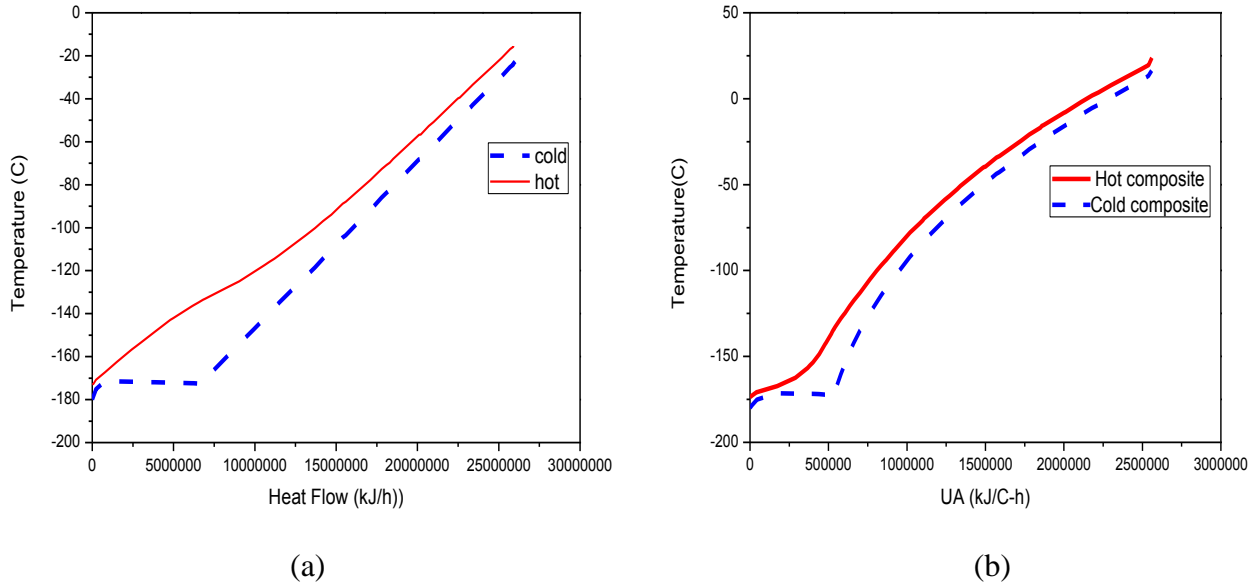


Fig.5.7. Main heat exchanger: (a) temperature-heat flow; (b) temperature-overall heat transfer coefficient (UA)

Fig.5.8. (a) and (b) shows the temperature versus heat flow and overall heat transfer of hot and cold composite of sub cooler. Both heat transfer and overall heat transfer coefficient increases with increase in temperature.

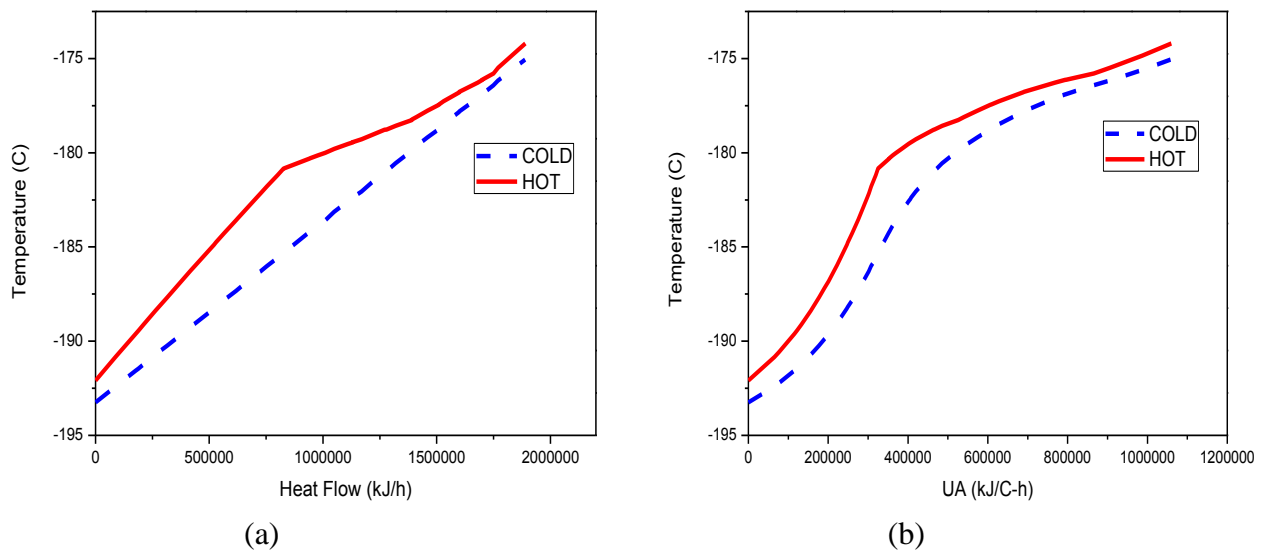


Fig.5.8. Sub cooler: (a) temperature-heat flow; (b) temperature-overall heat transfer coefficient (UA)

Table 5.1. Properties of each material stream in the plant simulation

		Material Streams									
		27	46	36	18	12	19	21	24		
Vapour Fraction		0.0000	1.0000	0.0000	1.0000	0.0352	1.0000	0.0000	0.0000	0.0000	
Temperature	C	-174.2	-193.2	-180.0	-170.8	-176.0	-178.2	-178.2	-175.8		
Pressure	kPa	539.0	133.0	140.0	539.0	538.7	535.0	535.0	538.7		
Molar Flow	kgmole/h	1536	3553	943.2	2476	1305	8.923	1293	943.6		
Mass Flow	kg/h	4.557e+004	9.976e+004	3.026e+004	7.169e+004	3.780e+004	250.0	3.623e+004	2.745e+004		
Liquid Volume Flow	m3/h	49.44	123.2	26.54	82.44	43.47	0.3100	44.90	31.26		
Heat Flow	kJ/h	-1.724e+007	-2.241e+007	-1.177e+007	-1.443e+007	-1.425e+007	-5.439e+004	-1.411e+007	-1.048e+007		
		22	23	25	26	17	52	55	50		
Vapour Fraction		0.0000	0.0140	0.0000	0.1041	1.0000	0.0000	1.0000	1.0000		
Temperature	C	-192.1	-193.4	-180.8	-191.3	-179.3	-180.4	-184.2	-180.3		
Pressure	kPa	530.0	133.0	534.0	134.9	135.8	138.0	123.0	138.8		
Molar Flow	kgmole/h	1293	1293	943.6	943.6	739.9	685.5	16.90	702.4		
Mass Flow	kg/h	3.623e+004	3.623e+004	2.745e+004	2.745e+004	2.143e+004	2.223e+004	675.1	2.290e+004		
Liquid Volume Flow	m3/h	44.90	44.90	31.26	31.26	24.64	19.32	0.4927	19.81		
Heat Flow	kJ/h	-1.515e+007	-1.515e+007	-1.076e+007	-1.076e+007	-4.346e+006	-8.504e+006	-7.456e+004	-4.022e+006		
		54	28	29	30	35	53	51	49		
Vapour Fraction		0.0000	0.0000	0.0000	0.0521	0.6553	0.0000	1.0000	0.0000		
Temperature	C	-180.4	-180.8	-184.6	-190.0	-188.0	-180.4	-180.3	-193.2		
Pressure	kPa	139.1	534.0	529.0	136.0	135.7	139.1	138.0	133.0		
Molar Flow	kgmole/h	686.5	1536	1536	1536	1536	685.5	702.4	9.787e-008		
Mass Flow	kg/h	2.226e+004	4.557e+004	4.557e+004	4.557e+004	4.557e+004	2.223e+004	2.290e+004	2.758e-006		
Liquid Volume Flow	m3/h	19.35	49.44	49.44	49.44	49.44	19.32	19.81	3.385e-009		
Heat Flow	kJ/h	-8.516e+006	-1.782e+007	-1.813e+007	-1.813e+007	-1.265e+007	-8.504e+006	-4.022e+006	-1.155e-003		
		58	57	56	LAR	ATM	47	37	38		
Vapour Fraction		0.0000	0.0000	1.0000	0.0109	0.0083	1.0000	0.0000	0.0000		
Temperature	C	-185.9	-184.4	-184.3	-186.1	-187.1	-175.0	-180.0	-180.0		
Pressure	kPa	115.0	120.0	117.4	101.3	101.3	130.0	140.0	140.0		
Molar Flow	kgmole/h	1.637e-005	16.90	16.90	16.90	1.637e-005	3553	4.461e-002	943.1		
Mass Flow	kg/h	6.444e-004	675.1	675.1	675.1	6.444e-004	9.976e+004	1.432	3.026e+004		
Liquid Volume Flow	m3/h	4.818e-007	0.4927	0.4927	0.4927	4.818e-007	123.2	1.255e-003	26.54		
Heat Flow	kJ/h	-0.1773	-1.816e+005	-7.456e+004	-1.816e+005	-0.1773	-2.052e+007	-556.6	-1.177e+007		
		43	42	44	45	48	11	4	20		
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	1.0000		
Temperature	C	-180.0	-180.0	-192.1	-183.3	13.25	-173.7	17.09	16.55		
Pressure	kPa	140.0	140.0	136.0	136.0	122.0	6370	550.0	527.0		
Molar Flow	kgmole/h	3.212e-002	1.249e-002	1.249e-002	4.461e-002	3553	1305	2476	8.923		
Mass Flow	kg/h	1.031	0.4009	0.4009	1.432	9.976e+004	3.780e+004	7.169e+004	250.0		
Liquid Volume Flow	m3/h	9.039e-004	3.515e-004	3.515e-004	1.255e-003	123.2	43.47	82.44	0.3100		
Heat Flow	kJ/h	-400.8	-155.9	-163.3	-564.0	-1.250e+006	-1.425e+007	-6.842e+005	-2575		
		16	15	10	40	41	13	6	9		
Vapour Fraction		1.0000	1.0000	1.0000	0.0000	1.0000	1.0000	1.0000	1.0000		
Temperature	C	-136.1	23.87	23.87	-179.9	16.55	60.18	24.00	30.57		
Pressure	kPa	727.0	730.0	6390	300.0	250.0	737.7	543.0	6395		
Molar Flow	kgmole/h	739.9	739.9	1305	943.1	943.1	739.9	739.9	1305		
Mass Flow	kg/h	2.143e+004	2.143e+004	3.780e+004	3.026e+004	3.026e+004	2.143e+004	2.143e+004	3.780e+004		
Liquid Volume Flow	m3/h	24.64	24.64	43.47	26.54	26.54	24.64	24.64	43.47		
Heat Flow	kJ/h	-3.567e+006	-6.795e+004	-6.609e+005	-1.176e+007	-2.547e+005	7.248e+005	-5.403e+004	-3.785e+005		
		3	5	14	8	7	2	1	AIR		
Vapour Fraction		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000		
Temperature	C	17.09	24.00	30.00	412.8	24.00	17.09	273.7	28.79		
Pressure	kPa	550.0	543.0	732.7	6400	543.0	550.0	555.0	101.3		
Molar Flow	kgmole/h	2045	2045	739.9	1305	1305	4521	4521	4521		
Mass Flow	kg/h	5.923e+004	5.923e+004	2.143e+004	3.780e+004	3.780e+004	1.309e+005	1.309e+005	1.309e+005		
Liquid Volume Flow	m3/h	68.11	68.11	24.64	43.47	43.47	150.6	150.6	150.6		
Heat Flow	kJ/h	-5.652e+005	-1.493e+005	6.556e+004	1.533e+007	-9.531e+004	-1.249e+006	3.352e+007	4.621e+005		
		GAN	GOX	Seal- Gas	LOX	LIN	31	32	34		
Vapour Fraction		1.0000	1.0000	1.0000	0.0000	0.0232	0.0521	0.0521	0.6553		
Temperature	C	13.19	16.04	15.37	-183.3	-195.7	-190.0	-190.0	-188.0		
Pressure	kPa	101.3	101.3	101.3	101.3	101.3	136.0	136.0	135.7		
Molar Flow	kgmole/h	3553	943.1	8.923	4.461e-002	9.787e-008	118.2	1418	118.2		
Mass Flow	kg/h	9.976e+004	3.026e+004	250.0	1.432	2.758e-006	3507	4.206e+004	3507		
Liquid Volume Flow	m3/h	123.2	26.54	0.3100	1.255e-003	3.385e-009	3.805	45.64	3.805		
Heat Flow	kJ/h	-1.250e+006	-2.547e+005	-2575	-564.0	-1.155e-003	-1.395e+006	-1.674e+007	-9.732e+005		
		33									
Vapour Fraction		0.5964									
Temperature	C	-188.2									
Pressure	kPa	135.7									
Molar Flow	kgmole/h	1418									
Mass Flow	kg/h	4.206e+004									
Liquid Volume Flow	m3/h	45.64									
Heat Flow	kJ/h	-1.219e+007									

Table 5.2. Energy streams in the plant simulation

Energy Streams								
		Q	Q-9	Q-10	Q-6	Q-4	Q-5	Q-2
Heat Flow	kJ/h	1.321e+007	4.557e+006	28.47	3.153e+005	7.788e+005	5697	6.592e+005
		Q-108	Q-3	Q-11	Q-1	Q-8	Q-7	Q-12
Heat Flow	kJ/h	1.542e+007	1.571e+007	3.306e+007	3.477e+007	4.552e+006	4.223e+005	-4888

Table 5.3. Composition of each stream in the plant simulation

Compositions									
	27	46	36	18	12	19	21	24	22
Comp Mole Frac (Nitrogen)	0.6128	0.9915	0.0000	0.7812	0.7812	0.9995	0.9990	0.7548	0.9990
Comp Mole Frac (Oxygen)	0.3730	0.0044	0.9889	0.2095	0.2095	0.0000	0.0000	0.2324	0.0000
Comp Mole Frac (Argon)	0.0142	0.0041	0.0111	0.0093	0.0093	0.0005	0.0010	0.0127	0.0010
	23	25	26	17	52	55	50	54	28
Comp Mole Frac (Nitrogen)	0.9990	0.7548	0.7548	0.7812	0.0000	0.0000	0.0000	0.0000	0.6128
Comp Mole Frac (Oxygen)	0.0000	0.2324	0.2324	0.2095	0.9466	0.0000	0.9238	0.9470	0.3730
Comp Mole Frac (Argon)	0.0010	0.0127	0.0127	0.0093	0.0534	1.0000	0.0762	0.0530	0.0142
	29	30	35	53	51	49	58	57	56
Comp Mole Frac (Nitrogen)	0.6128	0.6128	0.6128	0.0000	0.0000	0.9754	0.0490	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.3730	0.3730	0.3730	0.9466	0.9238	0.0151	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0142	0.0142	0.0142	0.0534	0.0762	0.0094	0.9510	1.0000	1.0000
	LAR	ATM	47	37	38	43	42	44	45
Comp Mole Frac (Nitrogen)	0.0000	0.0490	0.9915	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0044	0.9889	0.9889	0.9889	0.9889	0.9889	0.9889
Comp Mole Frac (Argon)	1.0000	0.9510	0.0041	0.0111	0.0111	0.0111	0.0111	0.0111	0.0111
	48	11	4	20	16	15	10	40	41
Comp Mole Frac (Nitrogen)	0.9915	0.7812	0.7812	0.9995	0.7812	0.7812	0.7812	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0044	0.2095	0.2095	0.0000	0.2095	0.2095	0.2095	0.9889	0.9889
Comp Mole Frac (Argon)	0.0041	0.0093	0.0093	0.0005	0.0093	0.0093	0.0093	0.0111	0.0111
	13	6	9	3	5	14	8	7	2
Comp Mole Frac (Nitrogen)	0.7812	0.7812	0.7812	0.7812	0.7812	0.7812	0.7812	0.7812	0.7812
Comp Mole Frac (Oxygen)	0.2095	0.2095	0.2095	0.2095	0.2095	0.2095	0.2095	0.2095	0.2095
Comp Mole Frac (Argon)	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093
	1	AIR	GAN	GOX	Seal- Gas	LOX	LIN	31	32
Comp Mole Frac (Nitrogen)	0.7812	0.7812	0.9915	0.0000	0.9995	0.0000	0.9754	0.6128	0.6128
Comp Mole Frac (Oxygen)	0.2095	0.2095	0.0044	0.9889	0.0000	0.9889	0.0151	0.3730	0.3730
Comp Mole Frac (Argon)	0.0093	0.0093	0.0041	0.0111	0.0005	0.0111	0.0094	0.0142	0.0142
	34	33							
Comp Mole Frac (Nitrogen)	0.6128	0.6128							
Comp Mole Frac (Oxygen)	0.3730	0.3730							
Comp Mole Frac (Argon)	0.0142	0.0142							

Table 5.1. Shows each material stream condition of the PFD, Table 5.2. Shows all energy streams, table 5.3. Shows the composition of each material stream, and table 5.4. shows the property of the air and main product component of plant

Table 5.4. Property of the main component.

Parameter	AIR	GOX	LOX	GAN	LAR
Temperature ($^{\circ}\text{C}$)	28.79	16.04	-183.3	13.19	-186.1
Pressure (kPa)	101.3	101.3	101.3	101.3	101.3
Molar flow (kgmole/h)	4521	943.1	0.04461	3553	16.90
Composition mole fraction(nitrogen)	0.7812	0	0	0.9915	0
Composition mole fraction (oxygen)	0.2095	0.98889	0.98889	0.0044	0
Composition mole fraction(argon)	0.0093	0.0111	0.0111	0.0041	1

5.1.5. Product recovery

The performance or efficiency of an air separation unit is calculated by its main product recovery. If oxygen is the main product, it may be define as the ratio of usable oxygen produced by the plant divided by the oxygen in the process air intake by the plant [3].

To increase the oxygen-product recovery, increase the reflux at the top of the upper column, but this depends on the following factor:

- The quality and quantity of liquid nitrogen reflux sent from the lower (high pressure) Column to upper column (low pressure column)
- The quantity and quality of the vapour rising to the top tray of the upper column

$$\text{Oxygen recovery (plant recovery)} = \frac{943.2 \text{ kgmole/h}(\text{oxygen produced})}{4521 \text{ kgmole/h} \times 0.2095(\text{air oxygen})} = 0.99562$$

5.1.6. Specific power

The specific power consumption of an air separation plant is calculated by its main product. Suppose oxygen is the main product, the specific power is define as ratio of total power consume by the plant to total oxygen produced.

$$\begin{aligned} \text{The main air compressor consume power} &= 9182 \text{ kW} \\ \text{And the booster compressor consume power} &= 4284 \text{ kW} \\ \text{Total power consume by the plant} &= 13466 \text{ kW} \\ \\ \text{Total amount of oxygen produced} &= 30260 \text{ kg/h} \end{aligned}$$

$$\text{Specific power consumption of the plant} = \frac{13466 \text{ kW}}{30260 \text{ kg/h}} = 0.44501 \text{ kW/kg/h of oxygen.}$$

5.2. Dynamic simulation analysis

We set the feed 2465kgmole/h in stream 18 and 1305kgmole/h in stream 12 in the flow controller (i.e. FIC-101 and FIC-102 respectively), run the simulation for 5 hour and get the following result

(a) **Flow controller:** The flow is controlled by valve reversely. FIC-101 controls the molar flow of stream 18 by a valve VLV-100 i.e. OP is the output (VLV-100) and process variable (PV) is the molar flow and SP is the set point.

In the Fig.5.9. The OP increases when the PV decreases below the set point and vice versa and the PV try to merge with the SP. Fig.5.10. has the same function for stream 12

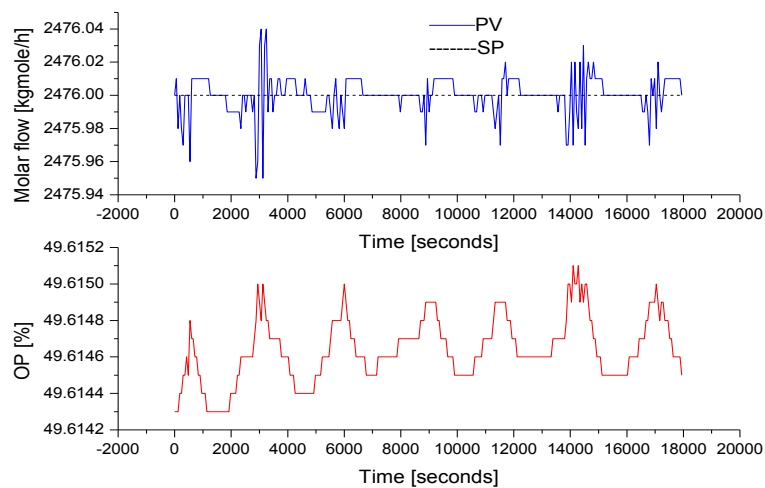


Fig.5.9. Flow and OP response of FIC-101 with time

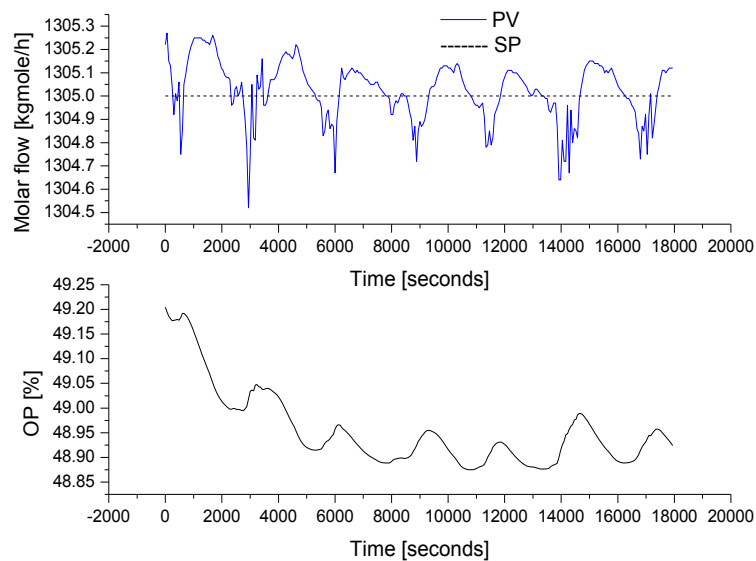


Fig.5.10. Flow and OP response of FIC-102 with time

(b) *Liquid level controller:* In Fig.5.11. LIC-101 opens the valve VLV-3 according to the liquid percentage level in the condenser of HP-Column which is proportionally connected. And LIC-102 controls the heat flow from the HP-column to boiler of the LP-column according to the liquid percentage level in the reboiler of the LP-column. Fig.5.12. LIC-102 shows the response of process parameter of according to tome.

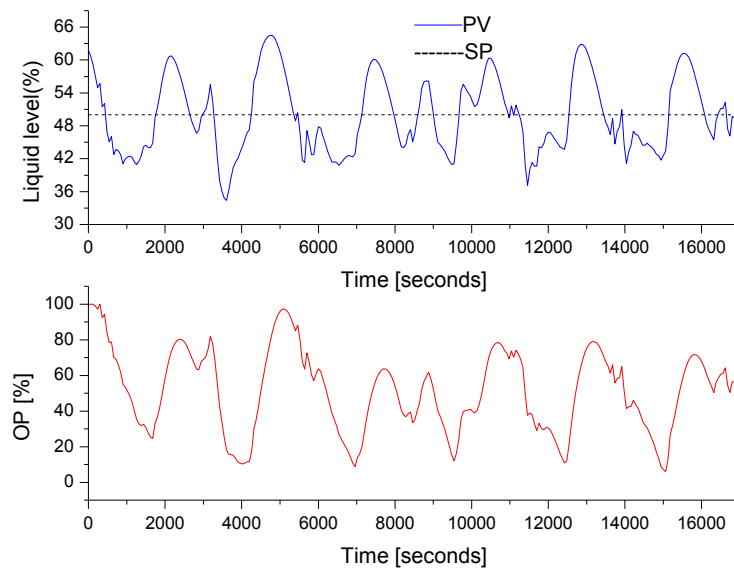


Fig.5.11. liquid level and OP response of LIC-101

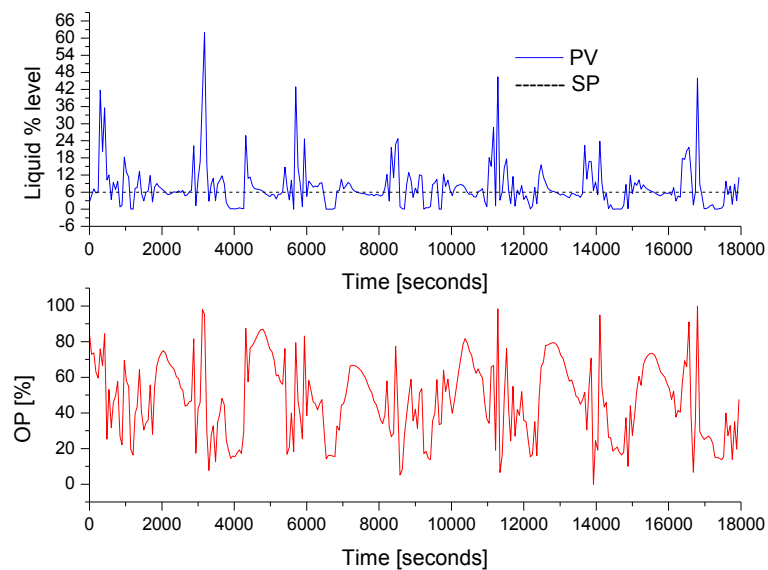


Fig.5.12. liquid level and OP response of LIC-102

(c) **Stage temperature controller:** TIC-201 controls the stage temperature of LP-column via VLV-105. If temperature increases the valve open and vice versa. In Fig. 5.13 OP is nothing but valve VLV-105 opening, PV is stage temperature of LP-column. The variation of process parameter with respect to time is shown below.

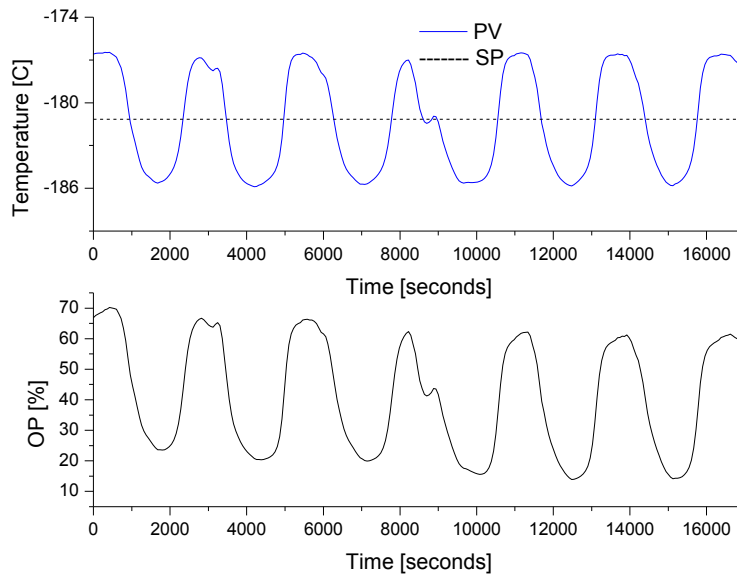


Fig.5.13. TIC-201, temperature and valve (VLV-105) response with respect to time.

(d) **Pressure controller:** In Fig.5.14. The set point pressure is 133kPa, the PV try to approach with the SP by the help of valve (VLV-108) opening and closing. (Which is proportionally connected).

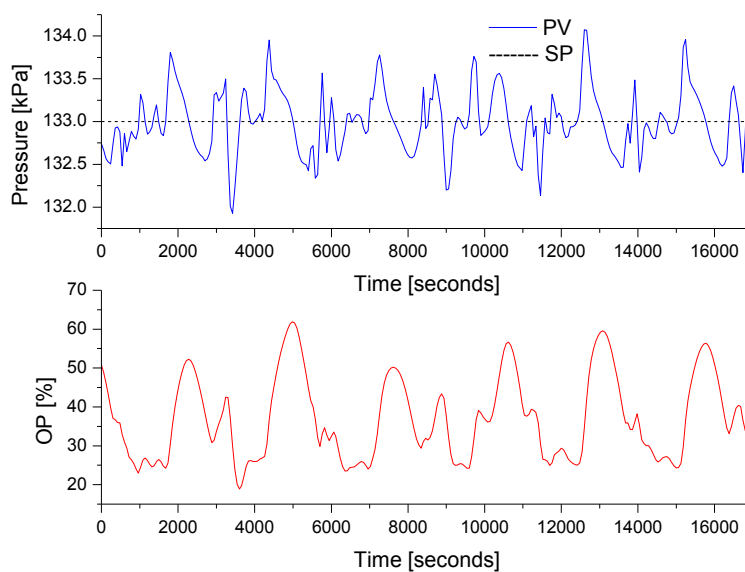


Fig.5.14. PIC-201, pressure (LP-column) and valve (VLV-108) response versus time

(e) *Effect on molar flow and mole fraction of oxygen product respect to time:* In fig. 5.15. The purity of oxygen is varying between 99.0% to 99.8% which is acceptable. And produced an average molar flow of 1000kgmole/h.

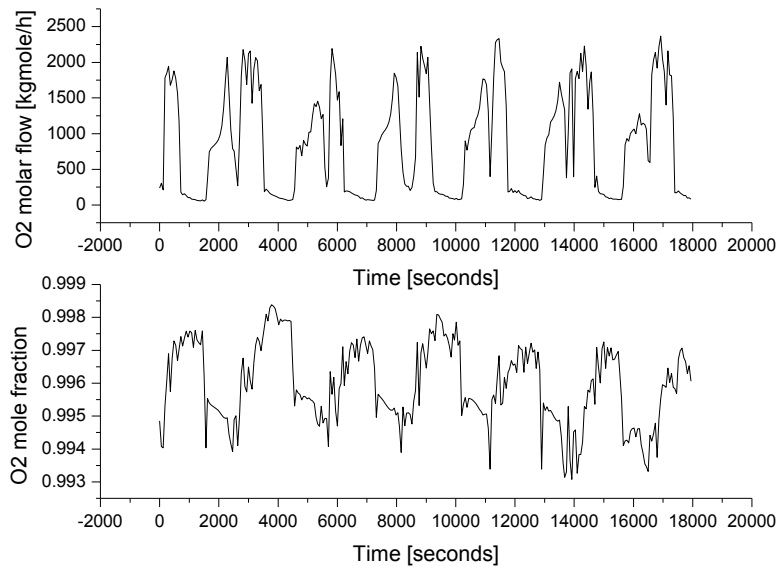


Fig.5.15. Variation of O₂ product molar flow and molar fraction with time.

(f) *Effect on molar flow and mole fraction of Nitrogen product respect to time:* In fig. 5.16. The purity of Nitrogen is varying between 99.80% to 99.99% which is acceptable. And produced an average molar flow of 3000kgmole/h.

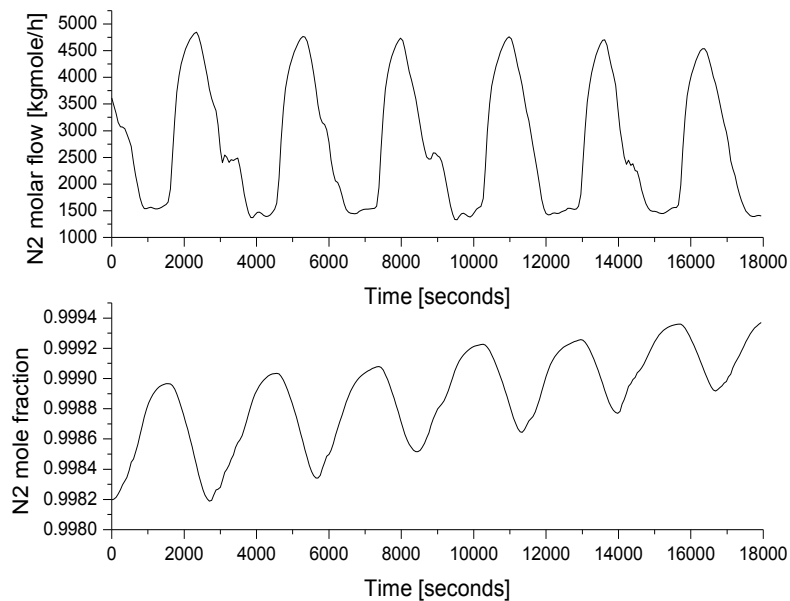
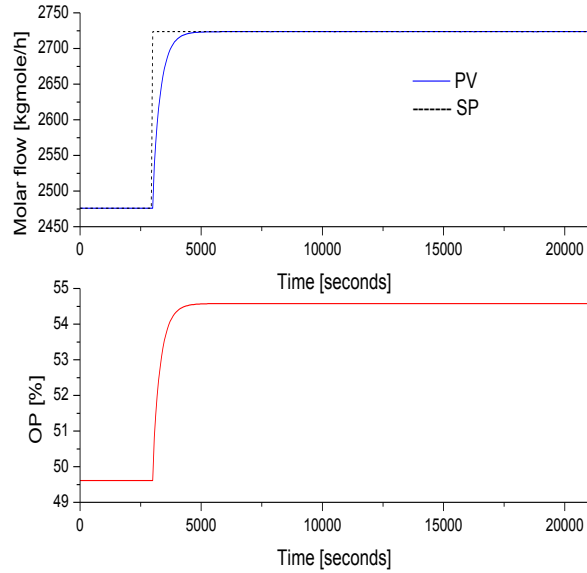


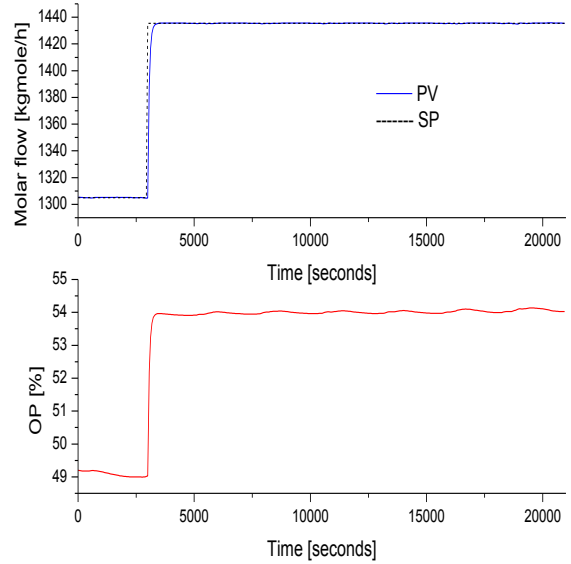
Fig.5.16. Variation of N₂ product molar flow and molar fraction with time

5.2.1. Feed molar flow disturbance analysis

(a) +10% feed molar flow disturbance:

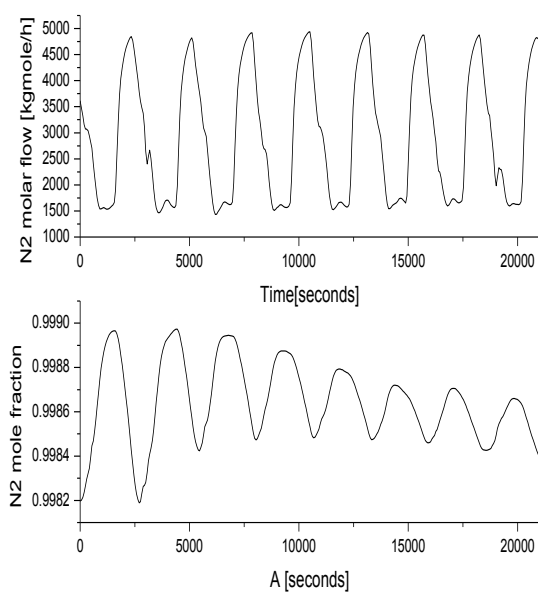


(a)

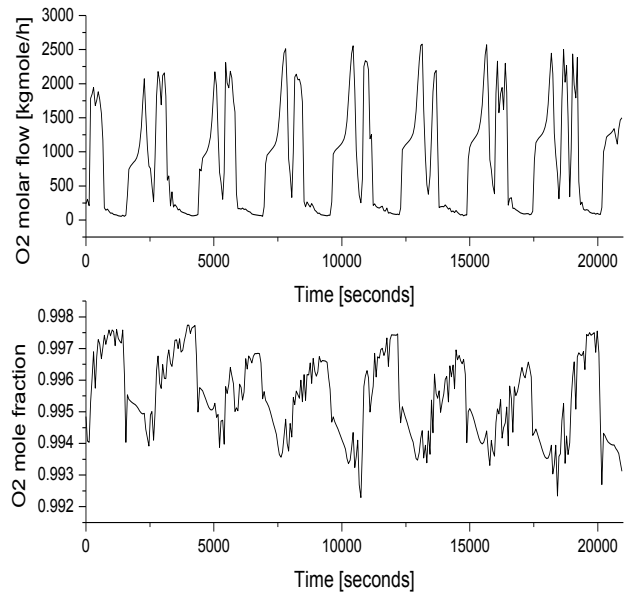


(b)

Fig.5.17. +10% feed molar flow disturbance at both Flow controller (a) FIC-101 (b) FIC-102 from the set point.



(a)



(b)

Fig.5.18. Response of (a) nitrogen and (b) oxygen product with change in +10% feed molar flow.

(b) -10% feed molar flow disturbance:

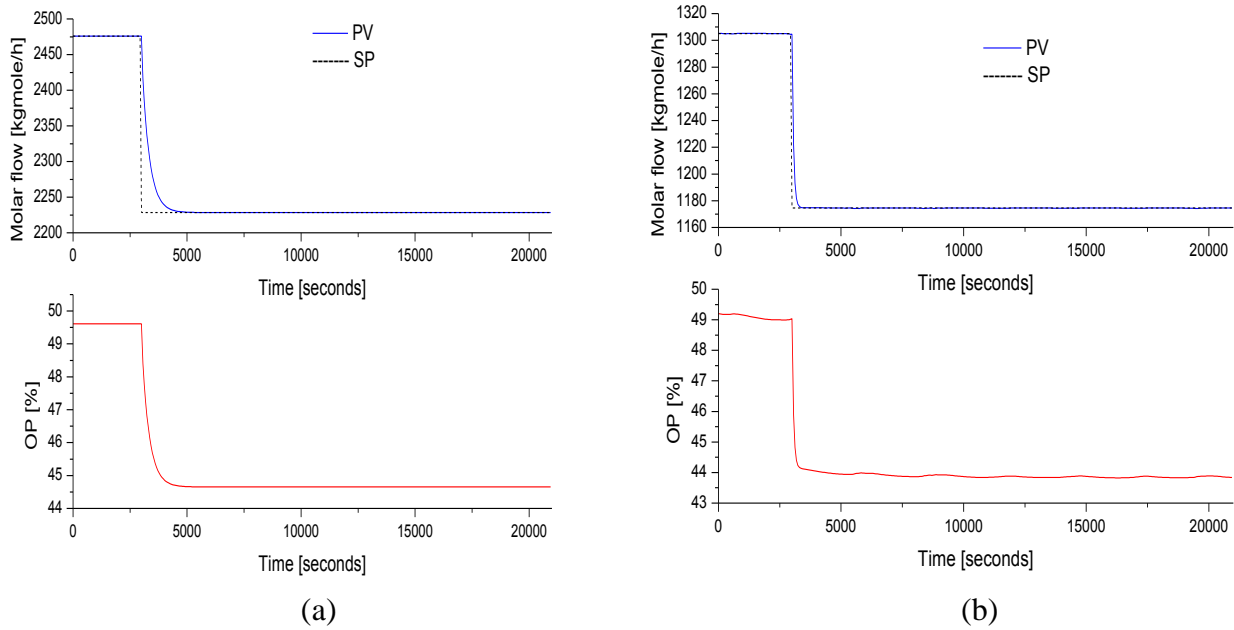


Fig.5.19. -10% feed molar flow disturbance at both Flow controller (a) FIC-101 (b) FIC-102 from the set point.

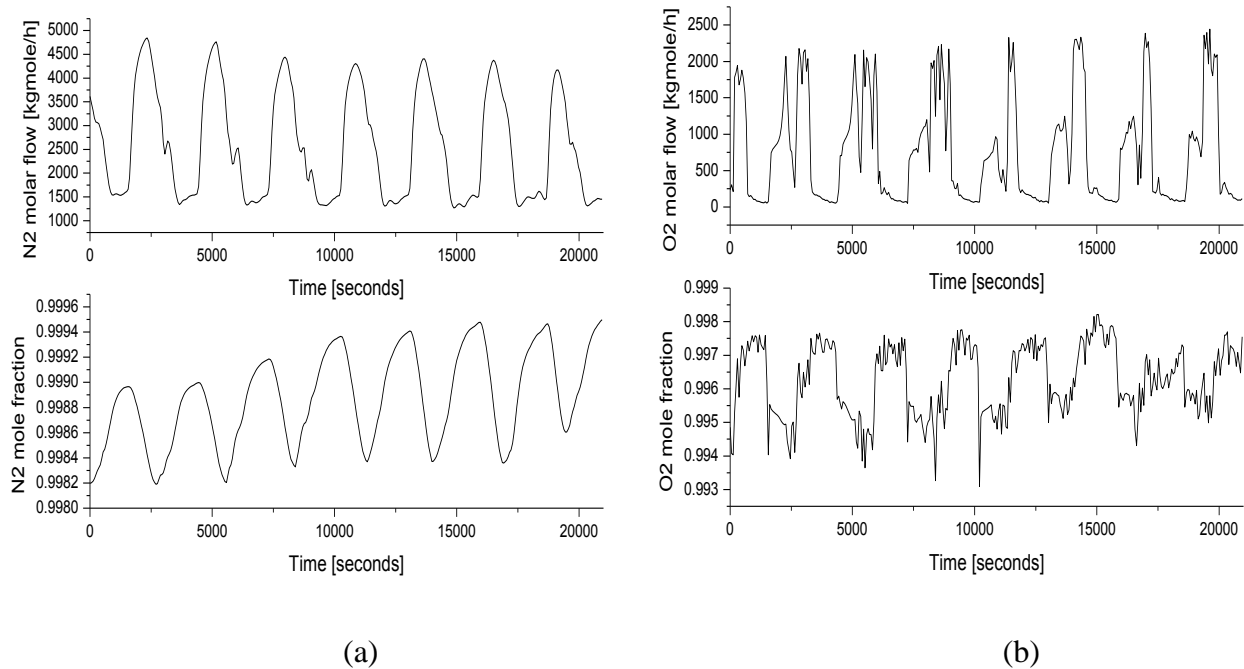


Fig.5.20. Response of (a) nitrogen and (b) oxygen product with change in -10% feed molar flow.

(c) +20% feed molar flow disturbance:

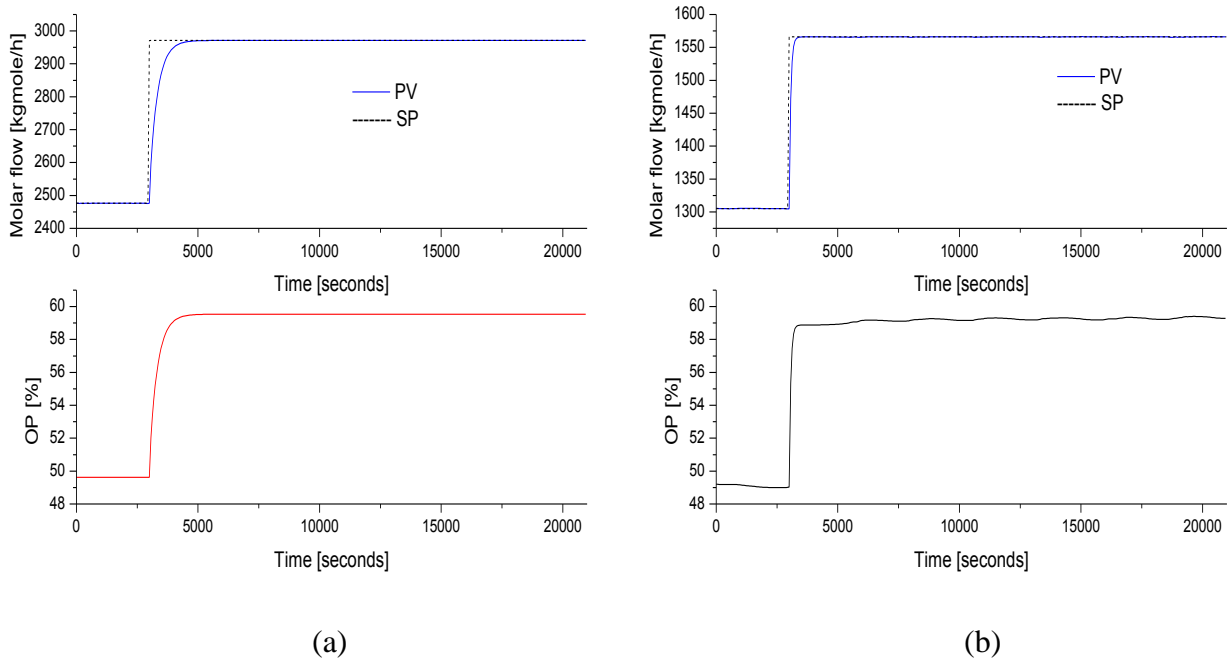


Fig.5.21. +20% feed molar flow disturbance at both Flow controller (a) FIC-101 (b) FIC-102 from the set point.

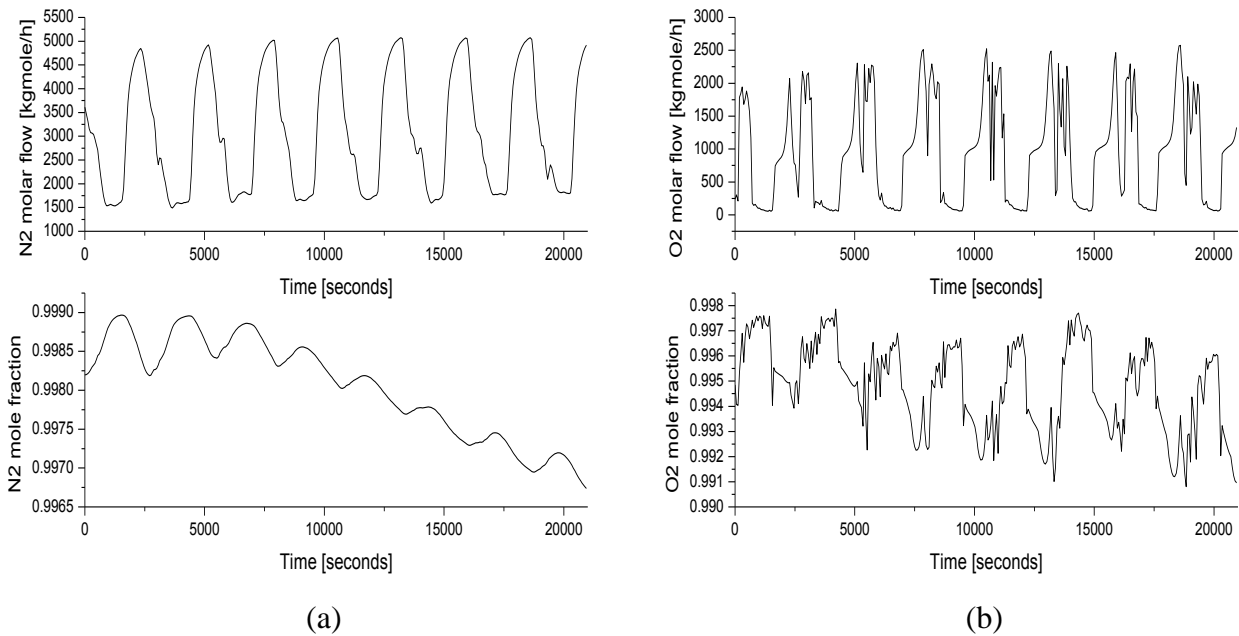
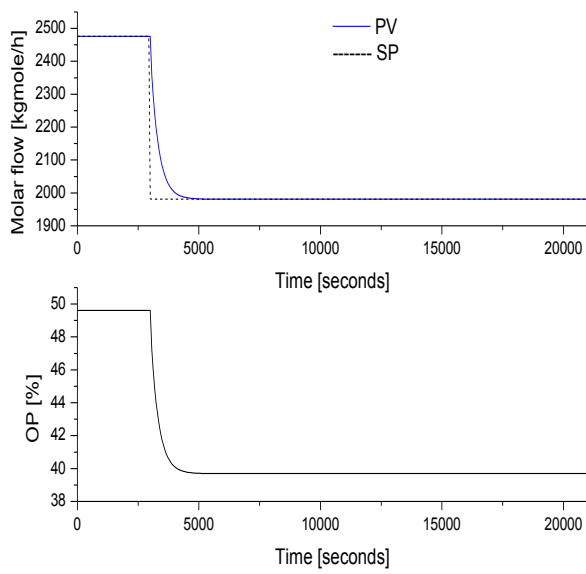
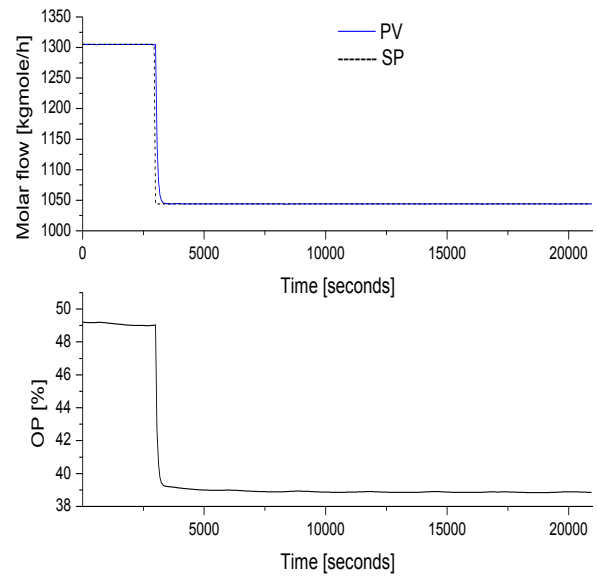


Fig.5.22. Response of (a) nitrogen and (b) oxygen product with change in +20% feed molar flow.

(d) -20% feed molar flow disturbance:

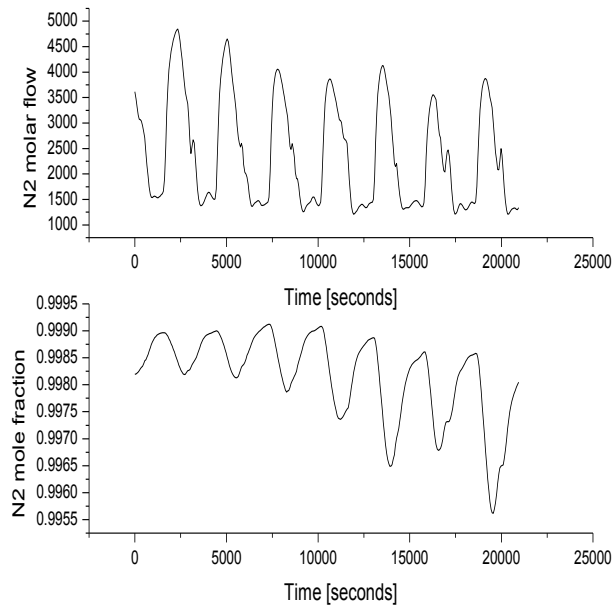


(a)

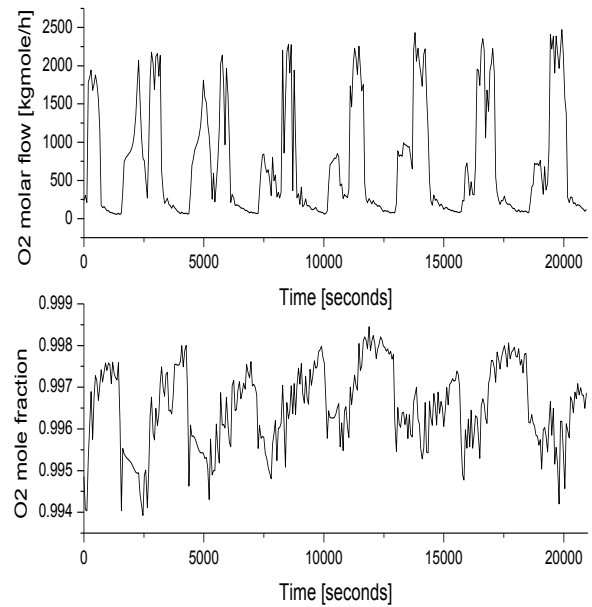


(b)

Fig.5.23. -20% feed molar flow disturbance at both Flow controller (a) FIC-101 (b) FIC-102 from the set point



(a)



(b)

Fig.5.24. Response of (a) nitrogen and (b) oxygen product with change in +20% feed molar flow.

We are giving a disturbance $\pm 10\%$ and $\pm 20\%$ feed molar flow to the flow controller i.e. FIC-101 and FIC-102 from their set point (2476 and 1305kgmole/h respectively) shown in figure 5.17, 5.19, 5.21 and 5.23 and corresponding response of purity and molar flow of nitrogen and oxygen are shown in figure 5.18, 5.20, 5.22, 5.24. When the set point (SP) changes the process variable (PV) also changes and try to merge with the SP by opening or closing the valve i.e. OP.

From the above graph, at $\pm 10\%$ variation of feed molar flow the purity of the nitrogen and oxygen are not so effected, but at $\pm 20\%$ variation of feed molar flow the purity of nitrogen and oxygen are affected i.e. continuously reducing.

Chapter 6

Conclusions

6. Conclusions

1. The air separation unit of Rourkela steel plant is simulated using Aspen Hysys software.
2. This model produces purity of Oxygen 98.889%, Nitrogen 99.1513%, Argon 100% and molar flow rate of Nitrogen 3553kgmole/h, Oxygen 943.1kgmole/h and Argon 16.90kgmole/h for an inlet Air flow rate of 4521kgmole/h at pressure of 101.3 kPa and temperature of 28⁰C which is economically suitable for steel plant.
3. The specific power consumption of this plant is 0.44501Kw/kg/h of O₂, and recovery of the plant is 99.562% based on oxygen in steady state case.
4. The power produced by the expander is 216kw which is used in the low pressure compressor and the heat produced by the condenser of HP-column is equal with heat required by the reboiler of LP-column. The boiling and condensing power required to the crude Argon and pure Argon column are well balanced by a bottom stream of high pressure column.
5. And also dynamic plant is controlled by using PID controller with optimum set point shown in table 4.2. And also observed the process parameter response with time. For a certain air flow rate this simulation model produces molar flow and mole fraction of product up to acceptable limit.
6. For this simulation, at $\pm 10\%$ variation of feed molar flow the purity of the nitrogen and oxygen are not so effected, but at $\pm 20\%$ variation of feed molar flow the purity of nitrogen and oxygen are affected i.e. continuously reducing

Chapter 7

Future work

7. Future work

1. The plant recovery and productivity can be increased and plant specific power can be reduced.
2. In dynamic simulation the other two columns i.e. crude argon column and pure argon column can also be controlled.
3. The model predictive controller, split range controller, ratio controller and DMC controller can also be used to control the dynamic plant.
4. The heat exchanger performance can also be studied.
5. To obtain optimum improvement of the plant is Dependent on continues progress in the research work and advanced Process control techniques.

Chapter 8

References

8. References

- [1] Barron, Randall F. "Cryogenic systems." Monographs on Cryogenics, New York: Oxford University Press, and Oxford: Clarendon Press, 1985, 2nd ed. 1 (1985).
- [2] Mahapatra P., and Wayne B. "Process design and control studies of an elevated-pressure air separations unit for IGCC power plants." American Control Conference (ACC), 2010. IEEE, 2010.
- [3] Frank G.K. "Industrial gas handbook." Boca ration London New York, CRC press Taylor and fracis group, 2006
- [4] Chakrabarti A.K. "Steel making." New Delhi, Prentice hall of India, 2007
- [5] Smith A. R., Klosek J. "A review of air separation technologies and their integration with energy conversion processes." Fuel Processing Technology 70.2 (2001): 115-134.
- [6] Latimer, R.E. "Distillation of air", chemical engineering progress, 1967.63(2): 35-69
- [7] Agrawal, Rakesh. "Synthesis of distillation column configurations for a multicomponent separation." Industrial & engineering chemistry research 35.4 (1996): 1059-1071.
- [8] Castle, W. F. "Air separation and liquefaction: recent developments and prospects for the beginning of the new millennium." International Journal of Refrigeration 25.1 (2002): 158-172.
- [9] Mahapatra P., Stephen E., Wayne B. "Dynamic Maximization of Oxygen Yield in an Elevated-Pressure Air Separation Unit using Multiple Model Predictive Control." Proc. of 10th IFAC International Symposium on Dynamics and Control of Process Systems (DYCOPS 2013), Mumbai, India. 2013.
- [10] Vinson, David R. "Air separation control technology." Computers & Chemical Engineering 30.10 (2006): 1436-1446.
- [11] Koros, William J., Rajiv Mahajan. "Pushing the limits on possibilities for large scale gas separation: which strategies?." Journal of Membrane Science 175.2 (2000): 181-196.

-
- [12] Anheden, M., Jinying Y., Smedt G. "Denitrogenation (or oxyfuel concepts)." *Oil & gas science and technology* 60.3 (2005): 485-495.
- [13] Burdyny, Thomas, Henning S. "Hybrid membrane/cryogenic separation of oxygen from air for use in the oxy-fuel process." *Energy* 35.5 (2010): 1884-1897.
- [14] Sapali, S. N., Raibhole V. N.. "Exergy Analysis of Cryogenic Air Separation Unit Integrated with Biomass Gasifier." *Proceedings of the World Congress on Engineering and Computer Science*. Vol. 2. 2013.
- [15] Amin, Ruhul, Aminul I., Rubaiyat I., and Shahidul I. "Simulation of N₂ Gas Separation Process from Air."
- [16] Bian, S., Khowinij, S., Henson, M. A., Belanger, P., Megan, L. (2005). "Compartmental modeling of high purity air separation columns." *Computers & chemical engineering*, 29(10), 2096-2109.
- [17] Latimer, R. E. "Distillation of air." *Chemical Engineering Progress* 63.2 (1967): 35.
- [18] Agrawal, Rakesh. "Synthesis of distillation column configurations for a multicomponent separation." *Industrial & engineering chemistry research* 35.4 (1996): 1059-1071.
- [19] Flynn Thomas M., "Cryogenic Engineering", Colorado, Oxford University Press, 1992.
- [20] Stoecker W.F, "Design of Thermal systems", Toronto, Tata McGraw Hill, 1986.
- [21] Bhanot S, "Process control".New Delhi,Oxford university press, 2008.
- [22] By Indirect, Thermochemical P. "Process design and economics for conversion of lignocellulosic biomass to ethanol." *Contract* 303 (2011): 275-3000.
- [23] Demirel, Yaşar. "Thermodynamic analysis of separation systems." *Separation science and technology* 39.16 (2004): 3897-3942.
- [24] Manenti, Flavio, et al. "Intensifying Air Separation Units." *chemical engineering* 35 (2013).
- [25] Huang, Rui, Victor M. Zavala, Lorenz T. Biegler. "Advanced step nonlinear model predictive control for air separation units." *Journal of Process Control* 19.4 (2009): 678-685.
-

- [26] Ang, Kiam Heong, Gregory Chong, Yun Li. "PID control system analysis, design, and technology." *Control Systems Technology, IEEE Transactions on* 13.4 (2005): 559-576.
- [27] Yan, Liwei, et al. "Energy Saving Opportunities in an Air Separation Process." (2010).
- [28] Aspen Hysys (Aspen ONEV8.5), Published by Aspen Technology.(2014)