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Research Article

Simulation Study for Energy Minimization and Performance Enhancement Using Cryogenic Plate and Packed Bed Column Networks for Air Separation

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Abstract

In this work, an energy efficient, high purity cryogenic air separation process containing heat integrated high pressure, low pressure plate type columns and packed bed argon recovery column were subjected to Aspen Hysys simulation in order to energy minimization and performance enhancement. Compressed liquefied air with composition 20.9% oxygen, 78.17% nitrogen, and 0.93% argon fed to the high pressure distillation column at temperature, pressure of -175.5oC, 5.5 bar respectively. The simulation results shows that process configuration containing high-pressure, low-pressure and argon recovery column can recover oxygen, nitrogen, and argon with purity of 97.93%, 98.28%, and 22.58% respectively with overall energy consumption of 93% for 800 MTPD capacities. The increase in number of plates from top to bottom will decrease the temperature from dew point to bubble point respectively.

Keywords: Cryogenic Separation; Distillation Column; Packed Column Temperature

Nomenclature

ARC: Argon Recovery Column; HPDC: High Pressure Distillation Column; HPPC: High Performance Process Control; IGCC: Integrated Gasification Combined Cycle; ITM: Ion Transport Membranes; LPDC: Low Pressure Distillation Column; PID: Proportional-Integral-Derivative; TPD: Tonnes per Day

Introduction

Industrial gases such as oxygen, nitrogen, and argon can be regarded as the “Blood” of modern chemical product industries [1-2]. Now a days a large number of chemical process industries are linked and interconnected with air separation units due to dramatically increasing demand of pure oxygen, nitrogen, and argon in chemical, metals, clay, glass, concrete products, refineries, welding, electronics and heat treating [3]. The dynamic performance of a plant is significantly affected by design and the failure in product quality standards is caused by poor dynamic performance of plant, economic instability, environmental constraints, and poor safety [4-6]. Usually industrial gasses consumers ask a question that which process technology is best for specific rate, purity, and optimum operating conditions. The three technologies; distillation, adsorption, and membrane separations that are currently exist for the air separation. Distillation is most mature of the three technologies that allows for both high purities (>99%) and large scale productions. Adsorption yields up to 95% purity but solvents limit, capacity, and capital cost are major issues. Membrane technology is the most recent developed technology including polymeric membranes and Ion Transport Membranes (ITM) both can produce purities of close to 100% both membranes however yet to be built for large scale gas separations [7-8]. The comparison of different air separation technologies is presented in Table 1.

Although for the high purity and large scale production of oxygen, nitrogen, and argon cryogenic distillation process remains the dominant choice [9-10].

Literature review

A double distillation column air separation process was presented for the recovery of oxygen, nitrogen, and argon at moderate pressure and result 5% more recovery and 10% less energy loss than traditional cryogenic air separation processes [11]. High purity nitrogen synthesis at medium pressure by cryogenic air separation process was focused by Agrawal K [12]. Better use of compressors minimized the half of the total energy loss was founded by Cornelissen R [13]. A review of developing economical and traditional oxygen production processes was described by Smith A.R [14]. The effect of vapor-liquid ratios in feed, liquid feed location, and side-cut location for argon on column efficiency and their optimum values for a commercial scale cryogenic air separation plant were discussed by Nobuaki E [15]. Optimization features, future profiles, and special features of scheduling problems were discussed by (Li T [16] by proposing a combined RTO and scheduling strategy for air separation process producing both gas and liquids. 91.75% purity of nitrogen separation from air by the aspen hysys simulation of Linde-Hampson Cycle was founded by Ruhul (Table 2,3) [17]. High purity dynamic cryogenic air separation column were modeled using aspen technology and non-linear model predictive control by Shoujun B [18]. An overview of functionalities methods in software packages, patents, and commercial hardware modules presented by observing that many PID controllers variants have been developed in order to improve the performance also suggested that in future PID controllers will be widely used for their easy set-up, optimum operability for enhanced productivity by Heong AK [19]. The challenges to high performance process control (HPPC) by operating the adsorption and cryogenic

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Table 1: Comparison of Different Air Separation Technologies.

Process	Status	Economical Range (≤TPD)	By Product Capacity	Purity limit (vol. %)	Start-Up Time
Adsorption	Semi-mature	<150	Poor	95	Minutes
Chemical	Developing	Undetermined	Poor	99+	Hours
Cryogenic	Mature	>20	Excellent	99+	Hours
Membrane	Semi-mature	<20	Poor	~40	Minutes
ITM	Developing	Undetermined	Poor	99+	Hours

Table 2: Design Parameters for High-Pressure and Low-Pressure Distillation Columns.

Parameters	HPDC	LPDC
Top Pressure (bars)	5	1.3
Top Temperature (°C)	-178.8	-193.4
Bottom Pressure (bars)	5.2	1.8
Bottom Temperature (°C)	-174	-179.2
Reflux Ratio	1.5	1.5
Number of Stages	19	45
Height of Column (m)	19	45
Diameter of Column (mm)	5.8	6.4
Area of Column (m^2)	26.1	31.26
Tray Type	Sieve	Sieve
Plate Thickness (mm)	3	3
Hole Diameter (mm)	3	3
Orifice Co-efficient	0.76	0.76
Downcomer Area (m^2)	0.19	4.84
Weir Length (m)	4.73	5.2
Weir Height (mm)	50	50
Weep Point (m/sec)	7.36	7.4
Minimum Operating Velocity (m/sec)	8.32	8
Liquid Flow Pattern	Single pass	Single pass

Table 3: Design Parameters for Argon Recovery Column (ARC).

Parameters	ARC
Top Pressure (bars)	1.2
Bottom Pressure (bars)	1.3
Top Temperature (°C)	-185.4
Bottom Temperature (°C)	-180
Reflux Ratio	26
Diameter of Column (m)	1.12
Number of Transfer Units	25
Height Equivalent Theoretical Plate	0.5
Height of Column	12.6
Packing Type	Random Packing-Berl Saddles 1/2″ diameter

processes at optimum efficiency over full range of steady-state and dynamic conditions and operability index values were discussed by David R [3]. Non-linear model predictive control was proposed to be essential for high performance of cryogenic air separation units over a wide range of conditions Huang [20]. A method was proposed for the simulation and optimization of air separation units to trace the physical feasibility of product (Juma H [21]. Steady-state and dynamic simulations of crude oil distillation plant using aspen plus were performed and compared with the experimental data by Liwei Y [22]. Seven principles of energy saving in cryogenic air separation processes were summarized by proposing a new air separation process with optimum energy consumption by the optimization of using multi-objective genetic algorithm and linear programming in order to overcome the energy loss and equipment deficiency also performed the aspen plus simulation of large-scale air separation unit based upon industrial operational parameters and process of a petrochemical company in order to analyze the actual performance of total site and energy analysis of major process Equipments Zhu Y [23]. Multi-scenario programming approach was used in order to reduce the energy consumption, improve performance, and to reduce uncertainty in optimization Van Der Ham L [24]. Two different processes one was two column based and 2nd was three column based cryogenic separation were studied by splitting the same feed into products in both processes and found that three column based process utilized 12% less energy than two column based process Mahapatra P [25]. Designing a pressure driven air separation unit for Integrated Gasification Combined Cycle (IGCC) based on model predictive controller by aspen plus and aspen dynamics in order to understand the performance of model predictive controllers it was suggested that PID based controller can optimize the plant dynamics Thomas [26]. Hybrid membrane process and cryogenic air separation unit was used to separation oxygen from air at large scale required for oxy-fuel combustion processes and found that in hybrid system vacuum pump arrangement to draw air through membranes has a high impact on power consumption of plant also founded that hybrid membrane process and cryogenic air separation unit is suitable for medium scale production Zhu Y [27]. Rigorous optimization tools were used to improve the process performance and maximize profitability Dustin J [28]. Five different air separation process configurations including EP-ASU, PLOX, GOX, LP-ASU, and IGCC were studied by and found that optimally designed for 100% nitrogen recovery combinations of EP-ASU with PLOX and EP-ASU with GOX have same performance. LP-ASU and PLOX combination is suitable for less than 50% recovery and EP-ASU with PLOX is suitable for greater than 50% recovery while IGCC found to be best for carbon dioxide capture Yasuki K [29]. Simulation based study concluded that self-heat recuperation can decrease 36% energy loss as compared to conventional cryogenic air separation processes Zuhua X [30]. Automatic feed variation system was developed in cryogenic air separation processes in order to meet the industrial gas consumer demands Van Dar Ham L [31]. The cryogenic air separation unit integrated with integrated gasification combined cycle (IGCC) was found that better heat integration by well use of heat of compression

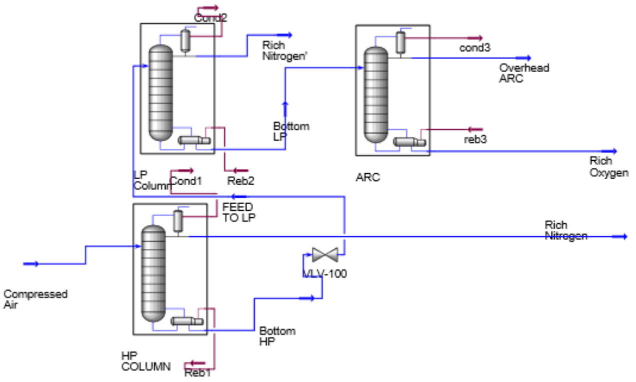


Figure 1: Configuration of Three Columns based Cryogenic Air Separation Process.

Table 4: Design Parameters for Condenser-Vaporizer Design.

Parameters	Values
Heat Flux (J/m^2.sec)	14.4
Required Heat Transfer Area (m^2)	55.6
Mean Temperature (K)	1.2
Tube Outside Diameter (mm)	38
Length of Single Tube (m)	1.5
No. of Tubes	301
Tubes Bundles Diameter (m)	0.95
Chest/Shell Diameter (m)	1.04
Tube Side Heat Transfer Coefficient (W/m^2.K)	13.61
Chest/Shell Heat Transfer Coefficient (W/m^2.K)	1.02 × 10^{-2}
Overall Heat Transfer Coefficient (W/m^2.K)	12.3

of column can increase the process overall efficiency significantly Rizk J [32]. Optimum configurations of 3-types of cryogenic distillation columns double adiabatic column, simple adiabatic column, and internal heat-integrated diabetic column were evaluated and found that double diabetic column has 23% less energy loss than other two types of configurations Chao F [33]. Double distillation column was studied for the 95% recovery of oxygen and found that it consume high energy than carbon dioxide capture also concluded that by using dual re-boilers in low pressure column can reduced 10% power consumption Chao F [34]. Two well-known energy saving techniques in distillation processes i.e. vapor recompression and distributed re-boiling were combined and applied to the conventional double distillation column for the cryogenic separation of air and found that significant reduction in energy loss, reduction in irreversibility's Stephen E [35]. Dynamic maximization of oxygen yield at elevated pressure of cryogenic air separation unit studied and found that the flow rate of liquid nitrogen stream connecting from high-pressure to low-pressure column has a significant impact on total oxygen yield Sapali S.N [36]. Medium purity cryogenic air separation unit integrated with biomass gasifier was subjected to the aspen plus and simulation results shows that 96.2% oxygen can be separated with energy consumption of 0.2435KW/scmh and proposed that the major source of energy loss is cold box (main heat exchanger), distillation column, and compressor Manenti [38]. Novel air separation processes and traditional air separation processes were compared and suggested the possibilities of further intensification, up gradation of recycle argon of rich streams, oxygen purity, and the possibility to energy generation through cryogenic air separation unit Lingyu Z [38].

By keeping in view the previous research we can conclude that researchers employed different simulations and optimization tolls using various software packages in order to develop optimum high performance controlled process configuration with optimum energy consumption, less equipment deficiency, high gas recoveries, less energy loss, and economical production with maximum profitability.

In this research work a novel process configuration has been developed using aspen hysys tools to recover oxygen, nitrogen and argon from air cryogenically at large scale with high purities with

Table 5: Simulation Results for Material Streams.

Name	Compressed Air	Rich Nitrogen	Bottom HP	Rich Nitrogen^1
Vapour Fraction	0.1401	0	0	0
Temperature (°C)	-175.5	-179	-174	-193.4
Pressure (bars)	5.5	5	5.2	1.3
Molar Flow (Kgmole/hr)	1150	589.1	560.9	328.2
Mass Flow (kg/hr)	3.30 × 10^4	1.655 × 10^4	1.675 × 10^4	9252
Liquid Volume Flow (ft^3/day)	3.24 × 10^4	1.729 × 10^4	1.517 × 10^4	9819
Heat Flow (KJ/hr)	-1.197 × 10^7	-4.496 × 10^6	-6.337 × 10^6	-3.893 × 10^6
Name	**Overhead ARC**	**Feed to LP**	**Bottom LP**	**Rich Oxygen**
Vapor Fraction	0	0.1061	0	0
Temperature (°C)	-182.1	-184.1	-177.1	-180.6
Pressure (bars)	1.2	2.2	1.8	1.29
Molar Flow (Kgmole/hr)	8.09	5.809	232.8	224.7
Mass Flow (kg/hr)	273.3	1.675 × 10^4	7499	7226
Liquid Volume Flow (ft^3/day)	194.6	1.519 × 10^4	5555	5380
Heat Flow (KJ/hr)	-9.904 × 10^4	-6.337 × 10^6	-2.878 × 10^6	-28.24 × 10^4

Table 6: Simulation Results for Streams Composition.

Name	Compressed Air	Rich Nitrogen	Bottom HP	Rich Nitrogen^1
Comp Mole Fraction (Oxygen)	0.209	0.0157	0.412	0.0147
Comp Mole Fraction (Nitrogen)	0.7817	0.9828	0.5705	0.9751
Comp Mole Fraction (Argon)	0.0093	0.0015	0.0175	0.0102
Comp Mole Fraction (Water)	0	0	0	0
Name	**Overhead ARC**	**Feed to LP**	**Bottom LP**	**Rich Oxygen**
Comp Mole Fraction (Oxygen)	0.7704	0.412	0.9721	0.9793
Comp Mole Fraction (Nitrogen)	0.0038	0.5705	0.0002	0
Comp Mole Fraction (Argon)	0.2258	0.0175	0.0278	0.0206
Comp Mole Fraction (Water)	0	0	0	0

Table 7: Simulation Results for Energy Streams.

Name	Cond1	Reb1	Cond2
Heat Flow (KJ/hr)	7.104×10^6	6.239×10^6	4.556×10^6
Name	**Reb2**	**Cond3**	**Reb3**
Heat Flow (KJ/hr)	4.122×10^6	1.461×10^6	1.417×10^6

Table 8: Detail of Unit Operations.

Operation	Operation Type	Feeds	Products	Ignored	Calculation Level
HP Column	Distillation	Compressed Air	Bottom HP	No	2500
		Reb1	Rich Nitrogen		
			Cond1		
LP Column	Distillation	Feed to LP	Bottom LP	No	2500
		Reb2	Rich Nitrogen^1		
			Cond2		
ARC	Distillation	Bottom LP	Rich Oxygen	No	2500
		Reb3	Overhead ARC		
			Cond3		
VLV-100	Valve	Bottom HP	Feed to LP	No	500

minimum overall energy loss.

Materials and Methods

Process description

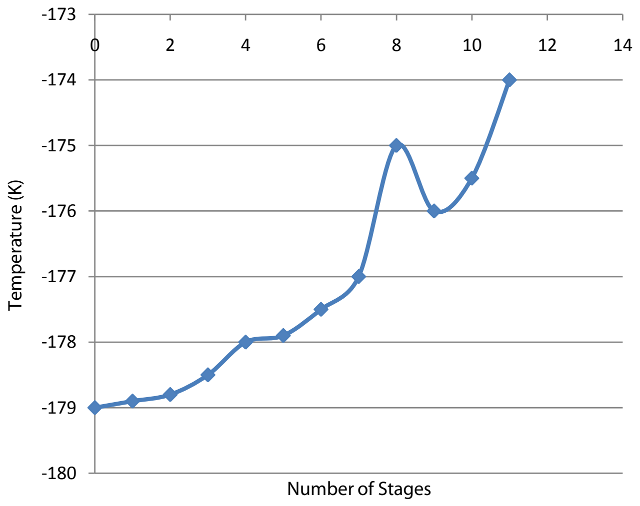
Carbon dioxide and water free liquefied air with composition 20.9% oxygen, 78.17% nitrogen, and 0.93% argon after preheated in main heat exchanger feed into the high pressure sieve tray distillation column having less pressure drop. The temperature of the gas stream decreased to its bubble point when passed through the coils that act as re-boilers. The temperature of the column was adjusted so that vapors are at their dew point and liquid at their bubble point. The bottom stream was oxygen richer and top stream was nitrogen richer. The top stream enters to the condenser-vaporizer operating between the high-pressure and low-pressure columns and yields 99.8% pure nitrogen. If liquid nitrogen was not required as major product at this stage this streams should be refluxed into low-pressure column. The bottom liquid oxygen product pressure is reduced to 2 bars and then introduced to the low-pressure column. In low-pressure column the liquid is re-boiled in the chest of condenser-vaporizer containing 95% oxygen, 0.2% nitrogen and 4.8% argon was sent to the argon recovery column. This packing type column recovers the 96% pure oxygen from the bottom and 27% pure argon from top of the column. The aspen hysys tools were used to draw the process flow sheet shown in Figure 1.

Material and energy balances were applied to the process and different design parameters of two distillation column, one packed column, and condenser-vaporizer were calculated using conventional McCabe-Thiele Method, Cornell's Method, Onda's Method, Motinski's Equation, Forster and Xuber Equation, and Zuber's Equation in order to run the process simulation using aspen hysys. The design parameters are tabulated and given below.

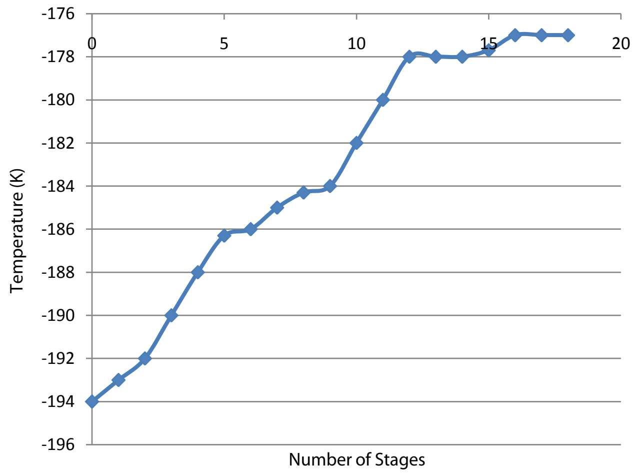
These design parameters when subjected to simulation using aspen hysys the results are summarized in Table 4-8.

Effect of temperature

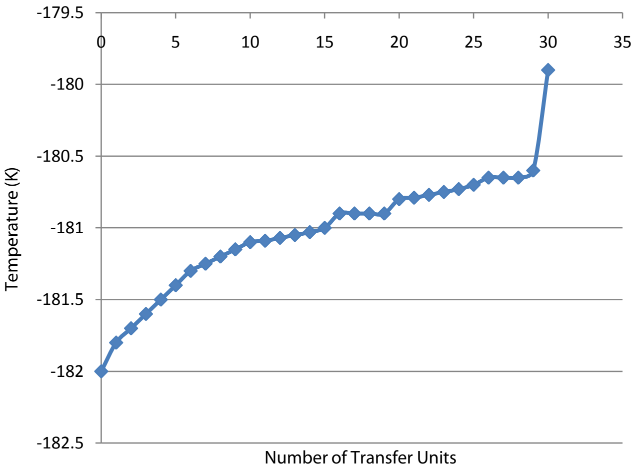
Simulations tools are used to in order to analyze plate to plate temperature profiles in high-pressure, low-pressure, and argon recovery columns and results shows that temperature of the system increase with increase from dew point to bubble point in number of stages in plate type distillation columns or transfer units in packed type column from top plate to bottom respectively. The results are shown in Graph 1,2 and 3.



Graph 1: Temperature Effect on Number of Stages in High-Pressure Column.



Graph 2: Temperature Effect on Number of Stages in Low-Pressure Column.



Graph 3: Temperature Effect on Number of Transfer Units in Argon Recovery Column.

Conclusion

In this research, simulation tools were used by using aspen hysys on three distillation columns based cryogenic air separation process in order to recover oxygen, nitrogen, and argon with high purity and after observing the simulation results, we concluded that this novel process configuration is suitable for 20.9% oxygen, 78.17% nitrogen, and 0.93% argon recovery from compressed liquefied air. The process also recovered 93% energy and 7% energy loss in overall process. Temperature effect on the number of plates has been investigated and found that the increase in number plates from top to bottom will increase the temperature from bubble point to dew point respectively.

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