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Simulation of Medium Purity Gaseous Oxygen Cryogenic Plant for Biomass Gasification by Aspen Plus

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Abstract

Cryogenic air separation plants are used for production of oxygen with purity over 99.5% (first grade oxygen) as required for welding, cutting, and medical. These plants are operates at low thermodynamic efficiency with specific power consumption in a range between 0.5- 0.6 kwh/scmh of O_2. Medium purity cryogenic air separation units are chiefly required for gasification. As air gasification produces poor quality syngas, oxygen is used as gasifying agent for biomass gasification. Biomass gasification with oxygen as gasifying agent has great potential in applications like IGCC (Integrated gasification combined cycle), chemical production and fischer-tropsch products. In this work, simulation of medium purity oxygen cryogenic air separation plant integrated with biomass gasifier is carried out by using Aspen Plus. Such cryogenic air separation plants (ASU) which produce oxygen in a range between 85-98% can be used economically for gasification. The cryogenic oxygen plant produces oxygen with purity 96.2 (%mole basis) with specific power consumption as 0.2435 kw/scmh of O_2. The performance parameters like recovery, purity, temperature, pressure and power consumption of cryogenic air separation unit are obtained. The parameters like syngas composition and heating value also predicted in simulation of biomass gasifier.

Keywords: ASU; ASPEN Plus; Biomass gasification; IGCC; Syngas

Introduction

The development of cryogenic ASU has been taken place through various stages. As the process cycle improvement is one of the areas for further development in cycle towards performance. The simulation of various unit operations with whole cryogenic ASU is carried out to understand thermodynamics of process. ASPEN Plus (Advanced System for Process Engineering Plus) is used for modeling cryogenic air separation plant and biomass gasification. It is a steady state chemical process simulator, which was developed at Massachusetts Institute of Technology (MIT) for the US DOE, to evaluate synthetic fuel technologies. It uses unit operation blocks, which are models of specific process operations (reactors, heaters, pumps etc.). The user places these blocks on a flow sheet, specifying material and energy streams. Aspen Plus is one of the most powerful and widely used process simulators in the process industry today. It has several features that make it very intuitive and user friendly. Its Graphic User Interface and Model Manager make an excellent guide for the user and allow for complete specifications and control at every stage of model development [1].

Most large scale applications do not require first grade oxygen (purity over 99.5%). It's too expensive also, as oxygen costs in such applications are critical. Different methods for production of second grade oxygen (medium purity) can be used [2]. The continuous development of air separation cycles has been taking place in terms of recovery, power consumption, purity, cost of manufacturing, ease of maintenance etc. [3-10]. Gasification involves the production of gaseous fuel mainly consisting of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), and with traces of methane (CH_4); with useable heating value by partial combustion of solid fuel. Biomass and inferior quality coal are having great potential for energy production. Currently, energy is recovered from these through combustion. The efficiency of these plants is very less. The coal/biomass gasification integrated with combined power cycle is offering higher efficiencies up to 60% [11]. An equilibrium model based on minimization of Gibbs free energy for rubber wood and simulated to get syngas composition [12]. Engineering equation solver (EES) is used to predict syngas composition in a small downdraft gasifier [13]. Thermodynamic equilibrium composition prediction is the important step in modeling the gasification process. An equilibrium model for biomass gasifier is developed and equilibrium relations are solved by using MATLAB for getting syngas composition and its properties [14]. Thermo chemical model has been developed to predict gas composition and performance of a biomass gasifier based on thermodynamic equilibrium concept for different materials [15]. Gasification of rice husk was tested in fluidized bed gasifier experimentally for studying various parameters of syngas like composition, temperature and heating value [16]. Clean syngas obtained from a gasifier can be used as fuel for a large combined cycle system for electricity generation, where the gasified fuel is first burnt in a combustion turbine–generator unit, and then, the hot exhaust gas from its gas turbine is used for generating steam to produce further power in a steam turbine–generator unit. The combination of a gasifier and a combined cycle is called the Integrated Gasification Combined Cycle. The multitude applications of syngas can be shown in figure 1 [17]. Energy and exergy analysis of gasification performed for obtaining performance and irreversibility's of the process [18].

The aim of the present work is to simulate medium purity oxygen cryogenic plant by using Aspen Plus and found out specific power consumption. It is also attempt to develop a model of biomass/coal gasifier with air/oxygen and steam as oxidizing agent by using Aspen Plus. Simulation of biomass gasifier based on Gibbs free energy minimization. The syngas is obtained with various parameters like syngas composition, temperature, heating value for different feedstocks as rice husk, wood pallets and Indian charcoal.

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Cryogenic air separation modeling

Distillation has long been used for air separation. The three major components of air - nitrogen, oxygen and argon - do not form any azeotropes and can be separated by simple distillation. Cooling is achieved through the Joule-Thomson effect, if we expand higher pressure air it cools down and can be partially liquefied. To simulate this process we use the Peng Robinson EOS.

The cryogenic air separation process is a tight integration of heat exchangers and separation columns which is completely driven by the compression of the air at the inlet of the unit. The air inlet stream is cooled to ambient temperatures with cooling water and further cooled against product and waste streams leaving the plant until partially liquefied. The liquefied fraction varies between 25 to 35 mol% depending on cooling water temperatures and compressor outlet pressure. This stream enters the bottom of a column that produces pure liquid nitrogen (Impurities 1 ppm) as overhead. The column has roughly 40 equilibrium stages including condenser and operates at high pressure. The cooling medium in the condenser is the oxygen bottom product produced in a second column. Thus, this second column must operate at a lower pressure to make the reboiler colder than the condenser of the high pressure column (typically by 1 Kelvin only). Thus, the pressures of both columns are linked mainly by the vapour pressures of nitrogen and oxygen and the temperature approach of the combined condenser/reboiler. In order for the oxygen to get out of the plant the bottom of the low pressure column are typically around 1.2 bars which set a pressure of at least 5.7 bars for the high pressure column. This requires the inlet compressor to deliver air at slightly higher pressures. These two columns share the same column shell to minimize the temperature difference between the condensing nitrogen and evaporating oxygen. The liquid bottom product of the High Pressure Column (HPC) is rich in oxygen. When this Rich Liquid (RL) is reduced in pressure, the Joule-Thomson (JT) effect causes this rich liquid to cool further. The rich liquid is fed to the Low Pressure Column (LPC). Additional refrigeration is obtained by compressing air in a second stage compressor to a high pressure and expands in expander. This air feeds directly to LP Column through JT valve. Finally, the low pressure column is refluxed with liquid nitrogen from the high pressure column, after having been flashed and cooled by the JT effect. The liquid oxygen bottoms is gasified and heated against the incoming air. The pure gaseous nitrogen of the top of the LPC is also heated to atmospheric conditions against the incoming air. The products of the Air Separation Unit are thus, gaseous nitrogen (GN_2) and oxygen (GO_2).

Gaseous oxygen plant

There is large demand for the oxygen in the decarburization of steel, in an electric arc and open- hearth furnaces and also in the bottom-blown Bessemer process of steel production in the steel industry. The steel making process needs gaseous oxygen to accelerate the oxidation and conversion of iron to steel. The oxygen purity required for above mentioned application is 99.99% (Mole% basis). Gasification is one of the applications which require huge quantity of pure oxygen with purity 94% to 96% (mole% basis). It is because air gasification produces a poor quality gas with regard to the heating value, around 4-9 MJ/Nm^3 higher heating value (HHV) while O_2 and steam blown processes result in a syngas with a heating value in the range of 10-20 MJ/Nm^3. In this simulation work, oxygen is obtained with purity 96.2% (mole% basis) from cryogenic air separation unit which can be used for biomass gasification. The simulation considerations are as mentioned below,

Simulation considerations

1.	Air flow	: 1000 scmh
2.	Compressor discharge pressure	: 4.2 bar
3.	LP Pressure	: 1.2 bar
4.	HP Pressure	: 4 bar

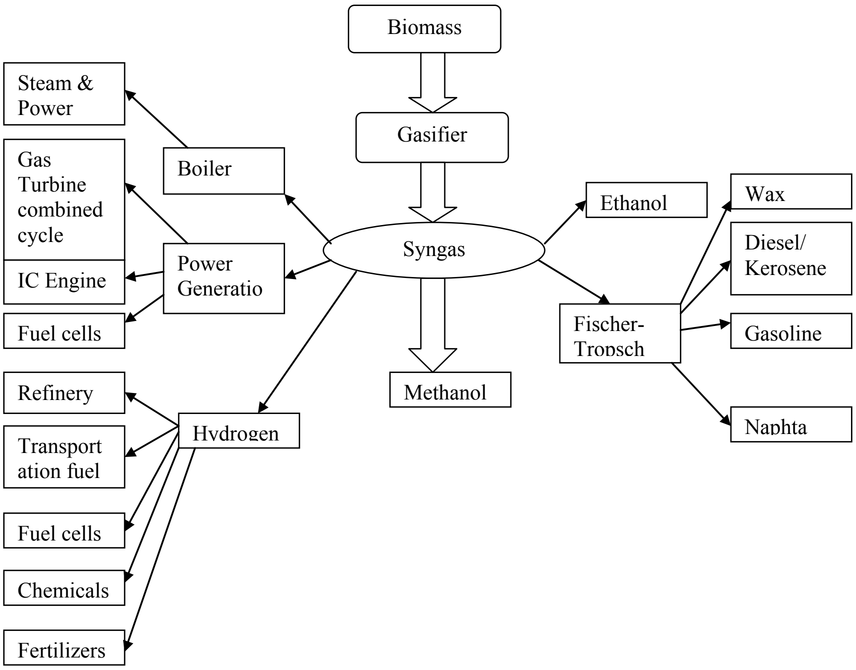

Figure 1: Multitude applications of syngas.

5. No. of stages in LP column : 56
6. No. of stages in HP column : 40
7. Heat leak : 15 kW

Simulation of cryogenic ASU for gaseous oxygen production

The cryogenic distillation of air is currently the only method available for the large oxygen production rates required for future fossil fuel gasification and oxy-fuel combustion with CO_2 capture. The current large scale users are the chemical, steel and petroleum industries. O_2 purities of up to 97% are favored for gasification application as this requires the much easier separation of N_2 from O_2. Production of 99.5% O_2 requires the more difficult O_2/Ar separation with up to double the number of separation stages in a distillation column. A flow sheet for the simplest type of cryogenic air separation system is shown in figure 2. Separation of over 95% of the O_2 in the air feed at 90% to 97% molar concentration is carried out in two distillation column thermally linked by a dual-function heat exchanger called as reboiler/condenser. This heat exchanger serves as a reboiler for the upper (HP) column and as a condenser for lower (LP) column. The LP column operates at low pressure as 1.2 bars which are close to ambient pressure to minimize energy use. The HP column operates at pressure 4 bar.

Filtered air is first compressed to 4.2 bars and cooled to 45°C temperature by water cooled heat exchanger. The compressed air then enters a main heat exchanger and is further cooled and partially liquefied by countercurrent heat exchanger with cold nitrogen and oxygen streams from the columns. Partially, liquefied air at 4.2 bar pressure enters the high pressure column. The separated N_2 gas condenses to provide reflux to the HP column and enters to the LP column after sub cooling in the sub-cooler. Up to 30% of the air is further compressed to

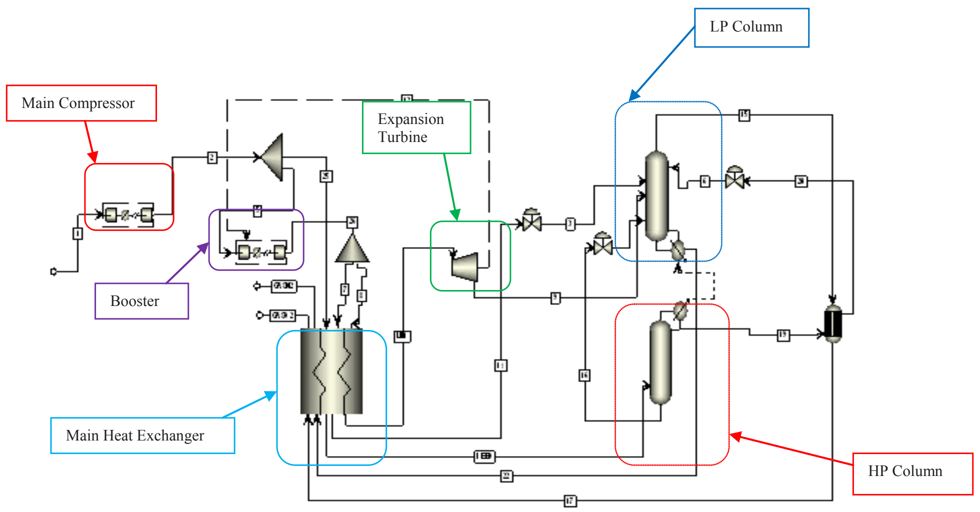

Figure 2: PFD of simulation of gaseous oxygen plant.

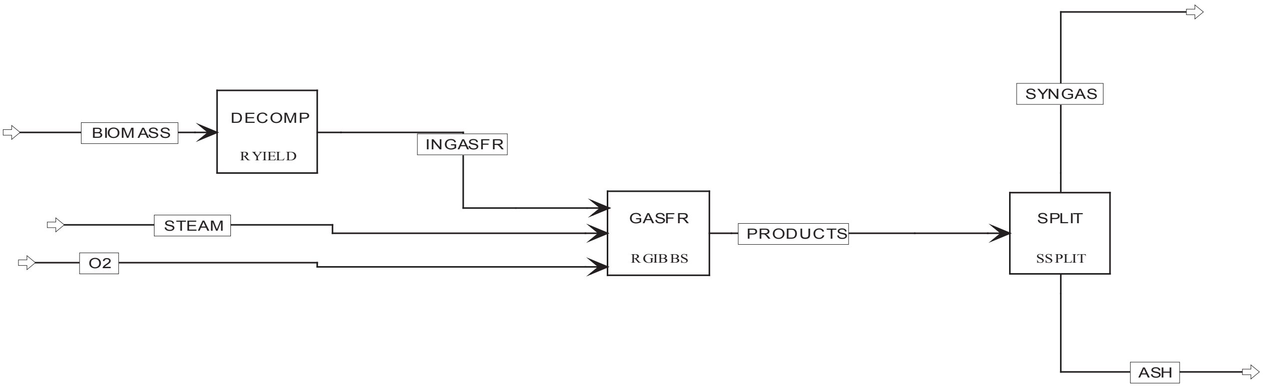

Figure 3: PFD of biomass gasification with air/oxygen as gasifying agent.

Feedstock	Proximate Analysis				Ultimate Analysis					
	FC	VM	Moisture	ASH	C	H	O	N	S	CL
Indian coal	39.83	26.74	5.9	27.53	56.09	3.58	6.05	0.72	0.24	--
Rice Husk	14.8	84.8	11.7	0.4	36.42	4.91	35.88	0.59	--	--
Wood pellets	10	85	8.55	0.574	48	8	46	--	--	--

Table1: Proximate and ultimate analysis of feedstocks.

a pressure of 50 bars which gives a positive temperature difference. The refrigeration balance on the plant is provided by expanding a portion of the high pressure air stream in a turbine. The discharge air stream from expander is feed to LP column. The O_2 rich liquid stream and a high pressure fraction of the air which has been liquefied are the feed streams to the LP column. The distillation separates an N_2 gas stream from top of LP column and a liquid O_2 stream from bottom of LP column are supplied to main heat exchanger and heated to ambient temperature, which cools and partially liquefies the air feed streams.

Modeling of biomass gasifier

Gasification is a process that involves many complex reactions that depend on chemical kinetics, reactor geometry, and many other parameters. As a result, the complexity of simulating gasification is simplified by modeling the process based on thermodynamic and chemical equilibrium. Equilibrium is a good assumption provided the residence time is long enough; however, in the case of most real world gasifiers this is not the case. A reacting system is at its most stable composition at chemical equilibrium. This state is achieved when the entropy of the system is maximized and its Gibbs free energy is minimized. Minimization of the Gibbs free energy of the products is the method used to calculate equilibrium in this work. Aspen Plus components in Aspen Plus provides a unit operation model called RGIBBS that calculates chemical and thermodynamic equilibrium based on minimizing the Gibbs free energy of the system. Components in Aspen Plus are classified as either conventional or nonconventional. Conventional components are ones with property data contained in the Aspen Plus component database. Non-conventional components are non-homogeneous substances that do not have a consistent composition and are not contained in the Aspen Plus component database. These components, which would include coal and biomass, must be given physical attributes, such as those defined by the ultimate, proximate, and sulfur analyses. Property methods must also be chosen to calculate the enthalpy and density of the substance. For this work, the property methods HCOALGEN and DCOALIGT were respectively chosen to calculate the enthalpy and density of biomass. These property methods use statistical correlations to calculate the specific heat, enthalpy, and density of coal and coal-derived substances based on the ultimate, proximate, and sulfur analyses. Because biomass can be represented as a technical fuel through these analyses, these property methods were also used for calculating the thermodynamic properties of biomass fuels. Furthermore, the property method HCOALGEN offers different options for how the enthalpy of formation of the component is calculated. For this work, the enthalpy of formation was calculated based on the higher heating value of the substance, which was specified by the user. The equilibrium reactor RGIBBS does not accept non-conventional components as reactants. As a result, the fuel must be decomposed to conventional components so they can be used by the RGIBBS block. The conversion is accomplished with an RYIELD block, labeled DECOMP, which is a reactor model that generates products based on known yields. The fuel feed stream enters DECOMP where it is decomposed into its elemental constituents. A FORTRAN calculator script interacts with the RYIELD block such that decomposition of the fuel is calculated based on the proximate and ultimate analyses of the nonconventional component. The carbon content of the feed is converted to solid carbon graphite. The hydrogen, oxygen, nitrogen, chlorine, and sulfur are converted to gaseous H_2, O_2, N_2, Cl_2, and S. Finally the moisture content is converted to liquid H_2O. These species are now contained in an intermediate stream called INPROCES, which then become the reactants for the RGIBBS block. An air stream representing the gasifying oxidant also enters REACTOR, and a products stream exits it. The heat stream QDECOMP connect the DECOMP and REACTOR and represents the energy required to decompose the solid fuel. Although QDECOMP interacts with REACTOR, the reactor is still considered to be adiabatic because DECOMP calculates the amount of heat required for decomposition and draws it from REACTOR.

Simulation of biomass gasifier with air/oxygen as gasifying agent

The simulation model of biomass gasification consists of two stages as biomass decomposition and gasification reaction with steam and oxygen. In decomposition, biomass is decomposed into its elements like C, H, O, S, N and H_2O. The Aspen Plus yield reactor RYIELD is used to simulate decomposition of the feed. The stream biomass is specified as non-conventional stream and ultimate and proximate analysis is given as input along with thermodynamic condition and mass flow rate. The Aspen Plus Gibbs reactor RGIBBS is used for partial combustion based on assumption that reactions of biomass elements with oxygen follow Gibbs` equilibrium. The products from RGIBBS reactor are fed to separator block. The top outlet stream which is called SYNGAS is composed of all the gases. The Process flow diagram (PFD) of biomass gasification with air/oxygen and steam is shown in figure 3.

Characteristics of feedstock's and simulation parameters of model

On the basis of process cycle design calculations, the main simulation parameters in cryogenic ASU integrated with gasifier model are: Oxygen flow rate- 10 kg/hr, Steam flow rate- 8 kg/hr, Input biomass mass flow-33.6 kg/hr and gasification pressure-1.05 bar. The proximate and ultimate analyses of different feedstocks are given in table 1.

Results and Discussion

In this simulation, a total of 209.78 scmh of gaseous O_2 product with 96.2% purity is produced which is safely used for gasification application. Gaseous N2 product with purity 99.9% is also produced at volumetric flow rate of 734 scmh. Heat duties of the reboiler of the LP column and condenser of the HP column ate matched by calculator block in Aspen Plus. The main compressor consumes 47.22 kW power and booster consumes 12.22 kW power, which is partially compensated

Parameters	FEED	GASN$_2$	GASO$_2$	LM1
Temperature K	95.5	300.1	302.8	283.1
Pressure bar	4.1	1.1	1.15	50
Vapor Frac	0.9	1	1	1
Mass Frac				
N_2	0.755	0.998	5 ppb	0.755
O_2	0.232	18 ppm	0.953	0.232
AR	0.013	0.002	0.047	0.013
Mole Flow scmh				
N_2	663.765	780.900	TRACE	114.792
O_2	178.33	0.012	209.78	30.814
AR	7.905	1.088	8.212	1.367
Mole Frac				
N_2	0.781	0.999	6 ppb	0.781
O_2	0.210	16 ppm	0.962	0.21
AR	0.009	0.001	0.038	0.009

Table 2: Simulation results of gaseous oxygen plant.

Feedstock	Gasifying Agent	Syngas composition(% mole)						
		H_2	CO	CO_2	H_2O	CH_4	N_2	CV(MJ/Kg)
Indian coal	Air	8.8	41.8	0.623	0.018	17.3	32	12.59
	Oxygen	15.3	60.1	0.003	0.492	0.23	0.8	19.55
Rice Husk	Air	22.9	18.4	13.0	8.3	0.8	36.6	5.49
	Oxygen	36.5	21.8	20.2	19.9	0.6	0.4	9.14
Wood pellets	Air	32.1	29.8	7.9	5.7	0.9	23.6	9.22
	oxygen	4.07	37.8	11.3	8.1	1.7	0.9	13.19

Table 3: Syngas composition of feedstocks.

by the power of 9.32 kW generated in the expander. The specific power consumption (SPC) is obtained is 0.2435 kw/scmh of O_2. The details simulation result of cryogenic ASU for oxygen production is shown in table 2.

Steady state simulation model of biomass gasifier in Aspen Plus predicts the composition of syngas. Syngas composition for different biomass with air and oxygen as gasifying agent are shown in table 3. It is observed that with oxygen as gasifying agent H_2 and CO in syngas composition is increased as it is not diluted with nitrogen. Heating value of syngas with air as gasifying agent is low as compared with oxygen as gasifying agent. Syngas with low heating value is suitable for applications like boiler and engine applications where as syngas with medium or high heating value suitable for F-T Process.

Conclusion

The simulation model of cryogenic ASU in Aspen Plus is produces oxygen with required purity and recovery. Oxygen is obtained with purity 96.2% which is economically suitable for biomass/coal gasification for getting syngas with a higher heating value. The specific power consumption is 0.2435 kw/scmh of O_2.

It is seen that air gasification produces a syngas with lower heating value, while O_2 and steam blown processes result in a syngas with a higher heating value. However, the use of oxygen does have other advantages such as operation at lower equivalence ratio, smaller equipment size of gasifier and downstream equipment, and possibly savings in compression cost of produced gas.

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