Mitigating an increase of specific power consumption in a cryogenic air separation unit at reduced oxygen production

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Abstract. Specific power consumed in a Linde double column air separation unit (ASU) increases as the quantity of oxygen produced at a given purity is decreased due to the changes of system requirement or market demand. As the plant operates in part load condition, the specific power consumption (SPC) increases as the total power consumption remains the same. In order to mitigate the increase of SPC at lower oxygen production, the operating pressure of high pressure column (HPC) can be lowered by extending the low pressure column (LPC) by a few trays and adding a second reboiler. As the duty of second reboiler in LPC is increased, the recovery of oxygen decreases with a lowering of the HPC pressure. This results in mitigation of the increase of SPC of the plant. A Medium pressure ASU with dual reboiler that produces pressurised gaseous and liquid products of oxygen and nitrogen is simulated in Aspen Hysys 8.6®, a commercial process simulator to determine SPC at varying oxygen production. The effects of reduced pressure of air feed into the cold box on the size of heat exchangers (HX) are analysed. Operation strategy to obtain various oxygen production rates at varying demand is also proposed.

1. Introduction
Cryogenic air separation plant separates air into oxygen (O₂), nitrogen (N₂) and argon (Ar) in gaseous and/or liquid form. These atmospheric gases have major application in steelmaking, fertilizer, petrochemical and coal gasification industries. Due to stringent implementation of pollution control norms around the globe, air separation plants are finding applications in power plants as well. In order to reduce the emission of carbon di-oxide (CO₂), power plants need to install carbon capture units [1, 2], which are classified as post-combustion, pre-combustion and oxy-fuel combustion [1-4]. In oxy-fuel combustion method oxygen is required at a purity of about 95% [3-7], which is supplied by cryogenic air separation unit.
The requirement of oxygen in an oxy-combustion based power plant fluctuates with the fluctuation in demand of electricity [8, 9]. Oxygen is usually produced by a Linde double column air separation unit (ASU), which is designed to produce oxygen (termed as recovery of oxygen) at a given flow rate and purity. As the demand of oxygen decreases, the total power consumption does not reduce proportionally and the SPC of the plant increases. This increases the cost of production of electricity in the power plant. In order to mitigate the increase of SPC in an ASU, the lowering of the operating pressure of the HPC (keeping the flow through the main air compressor the same) is an option. Operating pressure requirement of HPC can be reduced by adding a second reboiler in the low pressure column (LPC) of the same ASU [5-7] and shifting the first reboiler to a higher tray of LPC where the liquid has an increased nitrogen concentration. Agrawal and Woodward [5] analysed the dual-reboiler plant for generating pressurized pure nitrogen and the LPC was operated at higher pressure with the pressure of HPC remaining the same. Higginbotham et al. [6] compared power consumption of several configurations of ASU and suggested a dual-reboiler configuration which will produce pressurized nitrogen apart from oxygen. The pressurized nitrogen can be used in the system or employed to recover power in a turbo-expander. Fu and Gundersen [7] proposed a dual reboiler configuration for producing oxygen at 95% purity. Compression power in main air compressor decreased as the pressure of HPC was reduced. The irreversibility in the LPC was reduced as the composition profiles came closer. Gaseous oxygen, obtained at 1.2 bara, was compressed to 43 bara in a compressor to supply to oxy-fuel combustion power plant. If an ASU can be made to operate in dual-reboiler mode with the flexibility to convert in a single reboiler, the advantages of both configurations can be utilized according to different operational needs.

2. Objectives
Medium pressure (60 bara) dual-reboiler ASU is designed to supply gaseous oxygen (GOX) at 43 bara and gaseous nitrogen (GAN) at 23 bara to an oxy-fuel combustion based power plant [3, 4]. Designed plant also produces liquid oxygen (LOX) and liquid nitrogen (LIN) which can be used in any emergency. With the decrease in demand of oxygen in power plant, heat duties of condenser-reboilers (CR) have to be varied. Inter-relationship between the variation of CR duties and oxygen production has been evaluated. Heat Exchangers and condenser-reboilers of the basic ASU are resized to accommodate the fluctuating operating conditions caused by varying demand of oxygen. SPC is calculated at several CR duty to quantify the level of mitigation of SPC increase.

3. Methodology
3.1. Process description of ASU operating in single-reboiler mode
Air separation plant shown in Figure 1 was simulated in Aspen Hysys 8.6®, a sequential process simulator. Soave Redlich Kwong-Twu (SRK-Twu) fluid property package was used after verifying it with design data of a manufacturing plant [10]. Ambient air after passing through Main air compressor (MAC) and Pre-purification unit (PPU) is fed to the main heat exchanger. This compressed air cools close to its dew point temperature in main heat exchanger and enters HPC when the second CR (CR-2) is not functioning. Air separates to rich liquid (RL) having molar composition O₂ 38.2%, N₂ 60.1% and rest argon at the bottom and pure nitrogen vapour at the top. The top of high pressure column is heat integrated with the first CR (CR-1) a few plates above the CR-2. Nitrogen is condensed by a liquid mixture of oxygen and nitrogen at a few trays above the bottom of low pressure column via CR-1. Remaining gaseous pure nitrogen goes to main heat exchanger to recover its cold. Waste nitrogen from low pressure column sub-cools rich liquid air, impure liquid nitrogen, LIN product from HPC and LOX product from LPC to decrease vapour production upon flashing.

3.2. Process description of ASU operating in dual-reboiler mode
From Figure 1, for the heat integration to be possible in condenser-reboiler with a minimum temperature approach of 1 K, HPC operates at 5.3 bara and LPC at 1.3 bara, when ASU was operating
in single-reboiler mode. With the addition of CR-2, the plates between CRs start the process of separation due to which the liquid in CR-1 would have a higher oxygen content. This reduces the dew point temperature of liquid in CR-1 and thus, the saturation temperature of nitrogen vapour can be lowered facilitating the lowering of pressure of HPC.

Adding a second reboiler in the LPC brings the composition profiles closer reducing the irreversibility in the LPC. This reflects in the reduction of compression power. The recovery of oxygen from LPC at the desired purity reduces as a function of division of duty of CRs which has been analysed in present work. Hence for lesser production of oxygen from the ASU, the net power consumption will also reduce.

3.3 Assumptions and Terminologies used

The System operates at steady state. There is no pressure drop in the pipe lines. Heat in-leak is constant. The heat transferred from hot saturated vapor to the cold saturated liquid in the condenser-reboiler is known as the Condenser-Reboiler (CR) duty. UA of HX is the measure of its thermal size i.e the heat transferred in the HX for every 1 K of Log Mean Temperature Difference (LMTD). It is the product of overall heat transfer coefficient and the heat transfer area of HX. If deterioration factor F, which takes into account deterioration caused by thermal irreversibility, is taken into account then another term UA_{effective} is used. It is given by UA_{effective} = UA*F.
3.4 Non-dimensionalization of UA of HX

UA of HXs are non-dimensionalised by dividing it with \((m \cdot c_p)_{\text{air}}\) at 300 K, 1 bara which is the feed of air to the plant. As the air feed governs the size of the all the components of an air separation plant [11,12]. \((m \cdot c_p)_{\text{air}} = 39.78 \text{ kg/s} \times 1.005 \text{ kJ/kg} = 39.979 \text{ kW}.

So, \(n_{\text{non-dimensional}} = \frac{UA_{\text{effective}}}{m \cdot c_p \text{,air at 300 K & 1 bara}}\)

This non-dimensionalization should not be confused with NTU (Number of Transfer Units), because in NTU, UA is divided by average \((m \cdot c_p)\) of the minimum heat capacity stream of the heat exchanger and \(c_p,\text{average}\) is calculated at the mean value of specific heat of the fluid which is calculated at an average temperature. This temperature may be the harmonic or arithmetic mean of temperatures at several points along the length of heat exchanger [13].

3.5 Design of Medium pressure dual-reboiler ASU

ASU is designed similar to a manufacturing unit using its design data. ASU supplies gaseous oxygen (GOX) at 43 bara and gaseous nitrogen (GAN) at 23 bara to an oxy-fuel combustion based power plant and also produces liquid oxygen (LOX) and liquid nitrogen (LIN).

The medium pressure plant was designed in six steady state modes as shown in Table 1 to achieve maximum possible oxygen production at different operating pressures of HPC. For a certain heat duty of CR-2 to total CR duty there is only one pressure possible in HPC for heat integration to be possible in both CRs. Also for a particular division of heat duties between CRs, there is an unique maximum possible production of of \(O_2\) at 95% purity. While designing the plant it was observed that distribution of heat duty between CRs governs the closeness of composition profiles and thus irreversibility and \(O_2\) recovery. Thus heat duty of CR-2 was kept as an independent variable to design the plant and analyse each equipment.

While analysing the cycle flow rates of ambient air feed into main air compressor (MAC) unit, low pressure air coming from MAC unit into booster air compressor (BAC) unit, medium pressure (MP) air feed to turbine, LOX draw, pumped HP GAN at 23 bara, low pressure (LP) GAN, impure LIN feed to LPC were kept constant. Pressure of LOX at 41 bara, LIN 23 bara and high pressure (HP) air at 62 bara were also fixed.

| Pressure of HPC (bara) | \(O_2\) recovery (%) | Heat Duty of CR-2 to total CR duty | LOX pressure (bara) |
|------------------------|----------------------|----------------------------------|---------------------|
| 5.37                   | 98.6                 | 0 (no CR-2)                       | 1.41                |
| 5.12                   | 96.3                 | 0.06                             | 2.27                |
| 4.84                   | 94.3                 | 0.20                             | 2.08                |
| 4.44                   | 92.6                 | 0.27                             | 1.82                |
| 4.04                   | 90.8                 | 0.35                             | 1.55                |
| 3.74                   | 89.3                 | 0.41                             | 1.41                |

Heat duty of CR-2 cannot exceed 41% of total CR heat duty as it will lower \(\Delta T\) minimum in CR-2 below 1K because temperature difference between dew point temperature of air at 3.74 bara and LOX entering CR-2 will fall below 1 K. \(\Delta T\) minimum =1 K is taken as reference while designing WN2 subcoolers and CRs. We can also say that pressure of HPC cannot be lowered below 3.74 bara and also recovery cannot be decreased below 89% by only varying heat duty of CR-2. For further reduction \(O_2\) will have to be vented to atmosphere through WN2 stream, even though SPC would rise.

4. Results and discussion

4.1 Sizing of main HX
Flow rate of pumped LOX gasifying in main HX reduces with increase in CR duty ratio due to reduction of oxygen recovery from LPC. The net heat duty of main HX reduces. Reduction in heat duty of main HX requires to lesser high pressure air to be fed to main HX. Then for a fixed size of main HX requirement of HP air was calculated using simulation platform Aspen Hysys 8.6 as depicted in Figure 2. This graph can be used by engineers to control flow diversion to booster air compressor and diversion to low pressure stage of main air compressor.

4.2 Specific power consumption (SPC) comparison
As both pressure requirement of low pressure air and high pressure air reduces with the reduction in oxygen production, net power consumption also reduces as shown in Figure 3. Power calculations were done using characteristics curve of MAC and BAC units [14]. Power consumption was non-dimensionalised by dividing by mass of 95% purity oxygen produced from LPC. For a 10% decrease of oxygen production from ASU, SPC increases by 11% if oxygen is vented to atmosphere from WN2, however power consumption reduces by 9% when CR-2 operates at maximum heat duty. This results in increase of 1.5% SPC only.

4.3 Sizing of waste nitrogen subcoolers

![Figure 4](image4.png)

Figure 4. Variation of size of WN2 subcoolers having a $\delta T$ minimum approach = 1 K v/s heat duty of CR-2 to total duty of CR-2 and CR-1

![Figure 5](image5.png)

Figure 5. Variation of $\delta T$ minimum approach = 1 K for fixed UAs v/s heat duty of CR-2 to total duty of CR-2 and CR-1
Pressure of waste nitrogen remains constant, but pressure of rich liquid in first WN2 sub-cooler and pressure of impure liquid in second WN2 sub-cooler reduces. So saturation temperature of liquids reduces. Liquids are entering WN2 sub-cooler at lesser pressure but are leaving at same temperature for a fixed δT minimum approach = 1 K. So, size requirement of WN2 subcoolers reduces. Thus maximum size of subcoolers was fixed as geometrical parameter as depicted in Figure 4. For a maximum size of subcoolers as the pressure would reduce with increase in CR duty, the δT minimum approach will reduce causing higher efficiency of heat HX which may be seen in Figure 5.

4.4 Sizing of second condenser-reboiler
Dew point temperature of air reduces with decrease in pressure, but LOX at a purity of 95% in CR-2 boils at constant pressure so its bubble point temperature remains constant as may be seen from Figure 6. Due to this δT minimum approach reduces which leads to increase in size requirement of CR-2. From Figure 9, UA of CR-2 continuously increases, so maximum required UA of CR-2 was selected as geometrical parameter.

4.5 Operation scheme to obtain a desired heat duty in second condenser-reboiler for a fixed size and near constant flow of low pressure air

If same flow rate of air keeps flowing into CR-2 then for a fixed UA the duty cannot be changed. But by pumping liquid entering in CR-2 as shown in Figure 8 variable duty in CR-2 can be obtained just by controlling the opening of pressure control valve after CR-2 [15]. Because the temperature profiles of CR-2 adjust in such a manner that whole UA of HX is utilized i.e. size requirement of HX becomes a constant. When an HX operates with highly reduced flow rate of air then some part of HX becomes ineffective owing to higher irreversibility losses in that section. Also by pumping temperature profiles of HX come closer, this reduces irreversibility.
However according to pump characteristics, flowrate passing the pump will reduce for a higher pressure generation in pump at reduced CR-2 heat duty. However, liquid falling in the bottom section of LPC also changes due to change in boil-off generated in CR-1. Thus, plant characteristics and pump characteristics should match to control heat duty of CR-2. To match the pump characteristics a bypass line with a flow control valve is also proposed in Figure 1.

4.6 Variation of composition in the second condenser-reboiler
With the increase in boil-off at the bottom of the LPC, the plates between the CRs have higher vapour flow. This leads to higher separation in the plates between both CRs. The nitrogen content in the liquid at CR-1 location increases. Nitrogen has lesser saturation temperature than oxygen. This lowers the saturation temperature of liquid flowing into CR-2. So, nitrogen vapours from HPC can have a lesser pressure, as now vapours are required at lesser saturation pressure. This is the basis operating HPC at lesser pressure.

Liquid to vapour ratio in different sections in HPC and LPC shown in Figure 10 helps in understanding that separation in section between CR-1 and CR-2 is less at lower CR-2. Most of the separation occurs in top and middle section leading to irreversibility. Also L/V ratio reduces with increase in CR-2 duty due to which less separation occurs and recovery of O₂ reduces.

4.7 Sizing of first condenser-reboiler

![Figure 9](image9.png) Composition of liquid entering in CR-2 and liquid coming out from CR-2 v/s heat duty of CR-2 to total duty of CR-2 and CR-1

![Figure 10](image10.png) Liquid to vapour ratio in different sections of distillation columns v/s heat duty of CR-2 to total duty of CR-2 and CR-1

![Figure 11](image11.png) Variation of size of CR-1 and δT minimum v/s heat duty of CR-2 to total duty of CR-2 and CR-1

![Figure 12](image12.png) Pumping pressure requirement of liquid entering CR-1 to have a constant UA v/s heat duty of CR-2 to total duty of CR-2 and CR-1
With the increase in nitrogen content in liquid entering in CR-1 as may be seen from Figure 11, saturation temperature also reduces. Also nitrogen vapours that boil off reboiler-1 have lesser saturation temperature due to reduction in pressure of HPC. Due to this $\delta T$ minimum approach reduces which leads to increase in size requirement of CR-1.

4.8 Operation scheme to obtain a desired heat duty in first condenser-reboiler for a fixed size

Pumping of liquid entering CR-1 is not required similar to CR-2 as the net CR duty is governed by the net cold produced and utilized by products and equipments of the plant. By controlling CR-2 heat only CR-1 duty gets automatically fixed. So, CR-1 is designed for maximum requirement of UA only without employing a pump shown in Figure 12. Figure 12 was plotted to choose between control of CR-2 or CR-1. Control of CR-2 heat duty would be more precise as composition of LOX and air entering CR-2 remains constant as compared to CR-1 as shown in Figure 9, so it is easier to predict and control the heat duty CR-2.

4.9 Reduction of IL flowrate, reflux for LPC to attain 77% oxygen production

GOX production from dual-reboiler mode having maximum CR-2 duty was further reduced by reducing the flow of impure liquid (the reflux for LPC) draw from HPC. Requirement of HP air also reduces with lesser recovery of LOX from LPC, as lesser pumped LOX needs to be gasified in main HX.

5. Conclusions

Medium pressure dual-reboiler ASU is designed to produce GOX and GAN at required pressures of oxy-fuel combustion power plant. The plant also produces LIN and LOX. Operating pressure requirement of high pressure column (HPC) has been lowered from 5.6 bara to 4.0 bara as the recovery of oxygen is reduced from 99% to 89% just by varying heat duties of condenser-reboilers (CRs). Lowering of HPC pressure led to decrease of net power consumption by 7.6% but increase of SPC by 1.7% as compared to 11.1% increase of SPC without the presence of second reboiler. Then impure liquid (IL) feed to LPC was also reduced to attain 77% oxygen production to meet the off-peak demand of power plant based on oxy-fuel combustion.

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