

Energy Saving Air-Separation Plant Based on Exergy Analysis

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Air-separation units (ASUs) are widely used in various industries such as steel, chemistry and electronics. They require a very large amount of energy. Therefore, their energy consumption needs to be reduced further in order to help stop global warming. Shinko Air Water Cryoplant (SAC) has been conducting collaborative research with the University of Tokyo to develop a process that can greatly reduce the power consumption. The concept of "exergy" was introduced in this research as an index for evaluating the energy efficiency of a process. As a result, a new single-column rectification process has been developed and verified as requiring approximately 30% less energy than does the conventional double-column rectification process.

Introduction

In 1934, Kobe Steel produced an air-separation unit for the first time in Japan. For approximately 80 years since then, the company has been contributing to the growth of the industry as a manufacturer of air-separation units. Since 2004, Shinko Air Water Cryoplant, Ltd. (hereinafter referred to as "SAC"), a joint venture with Air Water Inc., has been supplying these air-separation units.

Air-separation units are mainly used for producing the oxygen, nitrogen and argon consumed in industries such as steel, chemistry and electronics. Some of these units consume power as high as several tens of megawatts, depending on the plants. Recent concerns over global warming from CO₂, etc. and soaring energy prices have significantly increased the need for further energy saving. Meanwhile, oxygen-enriched combustion technology is being adopted in the fields of steelmaking and thermal power generation. This combustion technology reduces the amount of heat lost in exhaust gas and improves the efficiency of combustion by burning with oxygen enriched air, and the demand for oxygen is expected to grow further. Thus, there is a need for an air-separation unit that can produce oxygen at low cost.

The performance of air-separation units has been improved considerably by adopting adsorbent for the front-end purification and by applying structured packing to their distilling columns.¹⁾ These air-separation units, however, can produce oxygen only at a power consumption rate as high as from 360kWh/kNm³-O₂ to 500kWh/kNm³-O₂,

versus the theoretical minimum consumption rate of approximately 70kWh/kNm³-O₂, and still leaves much room for further power reduction.²⁾

In an attempt to realize a process that can significantly decrease the power consumption of conventional air-separation units, SAC has conducted collaborative research with the University of Tokyo. This paper introduces a process analysis based on "exergy" as an index for evaluating energy efficiency. Exergy is an index representing the amount of energy that can be extracted as useful work under the standard conditions and is also referred to as effective energy (See Equation (1) further on in this paper).

As a result of the study based on exergy, converting the air-separation process from a double-column rectification process to a single-column rectification process and increasing the amount of thermal circulation enable a 30% power reduction in comparison with the conventional process.

1. Double-column rectification process

1.1 Conventional air-separation process (double-column rectification process)

Currently, large-scale air-separation units that separate air to produce oxygen and nitrogen adopt a process called a cryogenic separation process, in which air is liquefied, distilled (rectification) and separated into oxygen and nitrogen on the basis of the difference in their boiling points. Cryogenic separation is so called because the liquefaction of air occurs at a temperature from approximately -170°C to -190°C and the separation process is performed in a thermally-insulated cryogenic system. **Fig. 1** depicts the process flow of the cryogenic separation system generally used. Most air-separation units currently adopt a double-column rectification process, involving two rectification columns.

In a double-column rectification process, an air compressor is used to compress atmospheric air to approximately 450kPaG. The compressed air is introduced into a main heat exchanger, where most of the air is cooled to a temperature near the saturation temperature of -170°C. The saturated air is introduced into a high-pressure column (HP column) to be separated into oxygen-rich liquefied air and liquefied nitrogen. Meanwhile,

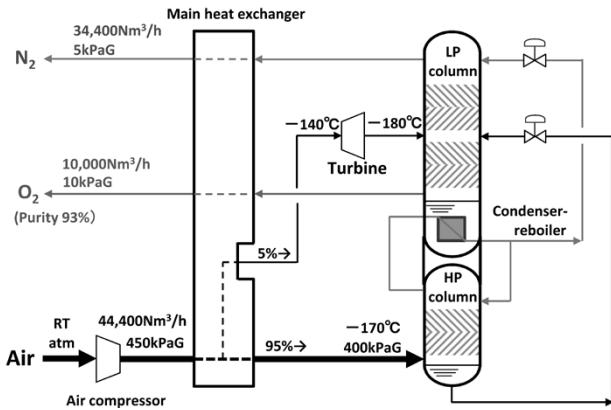


Fig. 1 Process flow for double-column rectification

the raw air partially extracted from the main heat exchanger at around -140°C is introduced into an expansion turbine and is adiabatically expanded until it reaches a low-temperature, low-pressure condition. This generates the cold energy required to maintain the apparatus at a low temperature. Next, the liquefied air and liquefied nitrogen are supplied into the respective zones of a low pressure column (LP column) as reflux fluids and are separated into highly-pure oxygen and nitrogen. The low pressure column is provided with a heat exchanger (Condenser-reboiler) at its bottom. This heat exchanger works both as a condenser for the HP column and as the reboiler for the LP column. The oxygen and nitrogen thus separated are warmed by the heat exchange with raw material air at the main heat exchanger and collected at room temperature.

1.2 Exergy analysis of double-column rectification process

An exergy analysis was conducted to identify which parts in a general double-column rectification process had a large energy loss. A large exergy loss means that energy is wasted. Thus it can be said that the smaller the exergy loss, the more superior the process.

Exergy (E) is defined by Equation (1):

$$E = H - H_0 - T_0(S - S_0) = \Delta Q - T_0 \Delta S \quad \dots \dots \dots (1)$$

H : Enthalpy of the system (kJ)

H_0 : Standard enthalpy (kJ)

S : Entropy of the system (kJ/K)

S_0 : Standard entropy (kJ/K)

T_0 : Standard temperature (K)

In order to calculate the amount of exergy loss in a heat exchanger, the latter half ($-T_0 \times \Delta S$) of Equation (1) is integrated with the whole temperature range of the heat exchanger:

$$\Delta E = \int_{T_0}^T (-T_0 \times \Delta S) dT = -T_0 \int_{T_0}^T (S_{(T)} - S_{0(T)}) dT$$

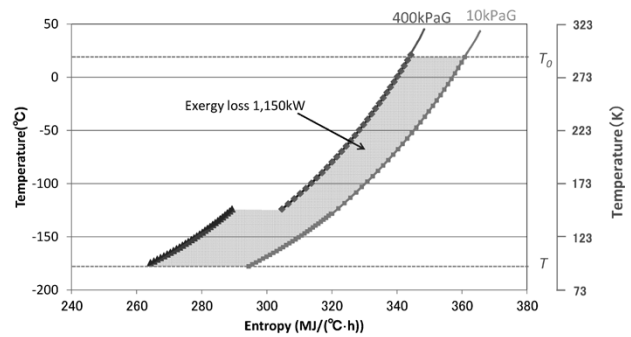


Fig. 2 T-S diagram of main heat exchanger in double-column rectification process

This means that in the T-S diagram shown in Fig. 2, the area encompassed by the plots on the high-temperature side and those on the low-temperature side becomes almost equal to the amount of exergy loss.³⁾ More specifically, the exergy analysis was conducted on an imaginary apparatus with the following specifications:

Oxygen flow rate: $10,000\text{Nm}^3/\text{h}$

Oxygen purity: 93% or higher

Oxygen pressure: 10kPaG

Nitrogen flow rate: $34,400\text{Nm}^3/\text{h}$

Nitrogen purity: 99% or higher

Nitrogen pressure: 5kPaG

Air flow: $44,400\text{Nm}^3/\text{h}$ (oxygen recovery rate 99.9%)

Air pressure: 450kPaG

Compressor efficiency: 70%

1.2.1 Amount of exergy loss for entire air-separation unit

In a double-column rectification process, the only apparatus to which external energy is supplied is the air compressor. The oxygen and nitrogen produced by this process are at a low pressure and at room temperature, conditions under which the exergy is almost equal to zero. Thus, the work applied to the air compressor is equal to the amount of exergy loss for the entire air-separation unit. On the basis of this, the amount of exergy loss for the entire air-separation unit is known to be 2,240kW.

1.2.2 Amount of exergy loss for main heat exchanger

The T-S diagram for the main heat exchanger in a double-column rectification process is shown in Fig.2. As described above, the amount of exergy loss for a heat exchanger can be calculated from T-S diagrams, and from the calculations performed using this diagram, it turns out to be 1,150kW.

Judging from the above, the amount of exergy

loss of the main heat exchanger, 1,150kW, accounts for more than half of the exergy loss of the entire air-separation unit, which is 2,240kW. Thus, decreasing the amount of the exergy loss of the main heat exchanger is the most effective way to save energy.

The T-S diagram in Fig. 2 shows that the plots for the high-temperature fluid (air) appear to the left of the plots for the low-temperature fluid (oxygen and nitrogen), indicating that this difference in entropy causes the increased amount of exergy loss. In this heat exchange, all of the raw-material air on the high-temperature side is at a pressure as high as approximately 400kPaG, while all of the fluid on the low-temperature side is as low as approximately 10kPaG. The greater this pressure difference is, the greater the amount of exergy loss for the heat exchanger. Therefore, in order to decrease the amount of exergy loss for the main heat exchanger, the pressure at the air compressor must be decreased so as to shift the plots of the high-temperature side to the right.

1.3 Problems of double-column rectification process

As described in 1.2, in order to decrease the amount of exergy loss for the main heat exchanger, the air-compressor pressure must be decreased. In a double-column rectification process, however, the condenser for the HP column is unified with the reboiler for the LP column. This is to allow the latent heat of condensation from the HP column condenser to be thermally recovered as the latent heat of vaporization of the reboiler at the bottom of the LP column, so as to establish rectification without supplying heat into the cryogenic system (Fig. 3). This configuration makes it difficult to significantly decrease the air-compressor pressure.

According to the second law of thermodynamics, in order to transfer heat from the HP column condenser to the LP column reboiler, the temperature at the top of the HP column (condenser) must be kept higher than the temperature at the bottom of the LP column (reboiler.)

In addition, for a given pressure, the boiling point of oxygen is higher than that of nitrogen. For example, the boiling point of oxygen at 30kPaG, the normal operating pressure of the LP column, is -180°C, while the boiling point of nitrogen is -194°C. Therefore, the pressure on the nitrogen side (HP column) must be raised to around 400kPaG, almost quadrupling the pressure on the oxygen side (LP column).

For the reasons described above, it is difficult to significantly decrease the air-compressor pressure,

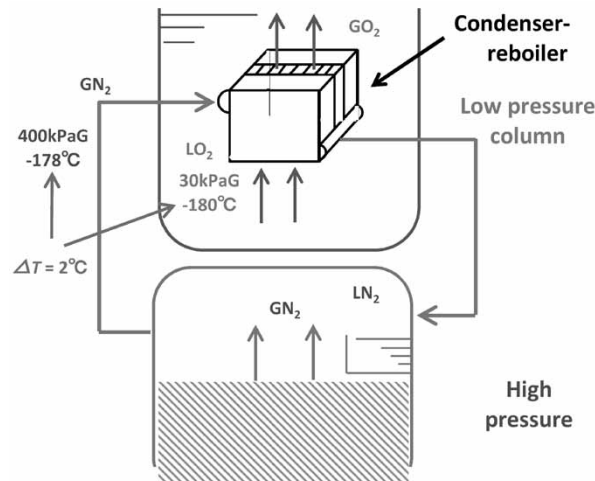


Fig. 3 Condenser-reboiler of double column rectification process

as long as we use a double-column rectification process consisting of two separate rectification columns and a condenser-reboiler coupled between them.

2. Single-column rectification process

2.1 Establishment of single-column rectification process

As described in 1.2, decreasing the amount of exergy loss in the main heat exchanger requires decreasing the air-compressor pressure. Now, the challenge is to establish a process in which the air-compressor pressure becomes equal solely to the pressure loss in the equipment and piping.

After due consideration, it was found that a single-column rectification process (Fig.4) comprising the following process elements can decrease the air-compressor pressure significantly.

- A single-column rectification is applied. This enables the air-compressor pressure to be equal solely to the pressure loss in the equipment and piping.
- A recycle nitrogen compressor is installed to provide a heat source for the bottom reboiler in the single-column rectification. Nitrogen is taken in at the top of the rectification column, and a part of the nitrogen is pressurized by the recycle nitrogen compressor so as to raise its saturation temperature. The pressurized nitrogen is introduced into the condenser-reboiler at the bottom of the rectification column, which vaporizes the liquefied oxygen at the bottom of the column.
- The latent heat of vaporization from the liquefied oxygen in the condenser-reboiler

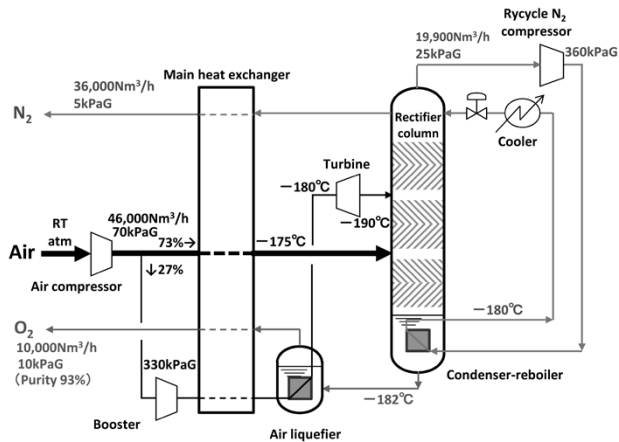


Fig. 4 Single-column rectification process

liquefies the nitrogen pressurized by the recycle nitrogen compressor. The nitrogen thus liquefied is supplied to the top of the rectification column as reflux.

- To liquefy a part of the air fed into the rectification column, that portion of air is pressurized by a booster compressor so as to increase its saturation temperature. This air is heat-exchanged with the liquefied oxygen taken from the bottom of the rectification column by an air condenser (Air Liquefier). This results in liquefying the compressed air and vaporizing the liquefied oxygen.

2.2 Exergy evaluation of single-column rectification process

As will be described below, the use of the single-column rectification process enables a significant decrease in the amount of exergy lost.

2.2.1 Amount of exergy loss for entire single-column rectification process

A single-column rectification process involves three compressors: namely, an air compressor, a booster for generating feed-liquefied air, and a recycle nitrogen compressor for generating the reflux of liquefied nitrogen. The amount of work applied (i.e., the pressure energy provided from outside) is 1,390kW in total.

The single-column rectification process is provided with a cooler on the secondary side of the condenser-reboiler for liquefying compressed nitrogen. The cooler is supplied with cold heat for the amount of power consumed by the recycle nitrogen compressor. The amount of exergy loss for this cold heat is 190kW.

Consequently, the amount of exergy loss for the single-column rectification process is equal to

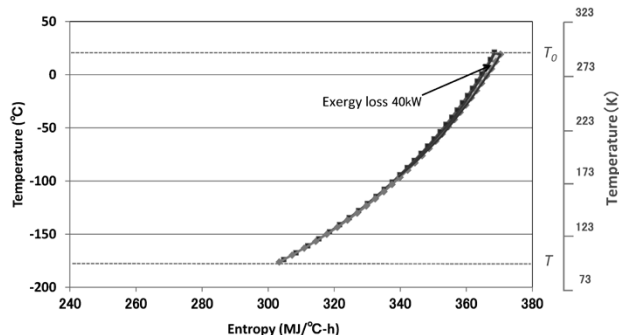


Fig. 5 T-S diagram of main heat exchanger in single column rectification process

1,580kW in total; i.e., the sum of the pressure energy applied and the exergy of the cold heat.

2.2.2 Amount of exergy loss for main heat exchanger in single-column rectification process

The T-S diagram of the main heat exchanger in the single-column rectification process is as shown in Fig. 5, which indicates an exergy loss of 40kW. This value is no greater than 5% of the amount of exergy loss for the main heat exchanger in the double-column rectification process. The exergy loss in this part is almost negligible.

As described above, the application of the single-column rectification process has significantly decreased the amount of exergy loss for the main heat exchanger, from 1,150kW to 40kW. The single-column rectification process, however, is additionally provided with a recycle nitrogen compressor and a booster compressor to establish the rectification. Part of the work applied by these compressors is added to the amount of work corresponding to the amount of exergy loss that is considered to occur outside the main heat exchanger in the double-column rectification process. Therefore, the amount of exergy loss outside the main heat exchanger is increased by 450kW, from 1,090kW to 1,540kW.

When the entire process is evaluated by the amount of exergy lost, however, the exergy loss of the single-column rectification process is decreased by 660kW (30%) compared with that of the double-column rectification process. In other words, the single-column rectification process is more efficient with a smaller exergy loss.

3. Energy-saving effect of single-column rectification process

A trial calculation was performed to see how much energy can be saved by using a single-column rectification process for an air-separation unit. The

Table 1 Comparison of power consumed by double column and single-column rectification processes

	Double column process	Single column process
Product oxygen (Nm ³ /h)	10,000	10,000
Air compressor		
Air flow (Nm ³ /h)	44,400	46,000
Pressure (kPaG)	450	70
Power (kW)	3,210	1,020
Booster compressor		
Air flow (Nm ³ /h)	-	12,500
Pressure (kPaG)	-	330
Power (kW)	-	610
Recycle N₂ compressor		
Nitrogen flow (Nm ³ /h)	-	19,900
Pressure (kPaG)	-	360
Power (kW)	-	370
Cold potential exergy		
Cold energy (kW)	-	370
Carnot efficiency (-)	-	0.73
Exergy (kW)	-	270
Power consumption (kW)	3,210	2,270

results are shown in **Table 1**.

Here, the power for the double column rectification process is consumed solely by its air compressor. The power for the single-column rectification process, on the other hand, includes the power consumed by the air compressor, booster compressor and recycle nitrogen compressor, taking into account the cold heat added by the cooler.

3.1 Power consumption of double-column rectification process

The power for the air compressor is estimated realistically by assuming its total efficiency to be 0.7, including impeller loss, motor power conversion efficiency and mechanical loss. The result gives 3,210kW, which corresponds to the power consumed by a double-column rectification process.

3.2 Power consumption of single-column rectification process

As with 3.1, assuming the total efficiency of the air compressor, booster and recycle nitrogen compressor to be 0.7, the total power consumed

by these compressors is estimated to be 2,000kW. Assuming the exergy of the cold heat to be consumed power, the cold heat is evaluated to be 270kW. The total of these values, 2,270kW, gives the power consumed.

From the above, the single-column rectification process consumes 30% less power (smaller by 940kW) compared with the conventional double-column rectification process. Hence the high efficiency of the single-column rectification process has been verified.

Conclusions

This study indicates that a single-column rectification process with an increased amount of thermal cycling is an energy-saving process that can decrease the power consumption by approximately 30% compared with a conventional double-column rectification process.

The efficiency improvement of an air-separation unit not only results in energy-saving for the unit itself, but also represents technology that can contribute to large-scale energy saving through oxygen-enriched combustion and the like. This is considered to make its technical development even more meaningful.

Kobe Steel intends to use process simulation to resolve the issues involved in implementing this process as an actual plant and to develop highly-efficient air-separation units.

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