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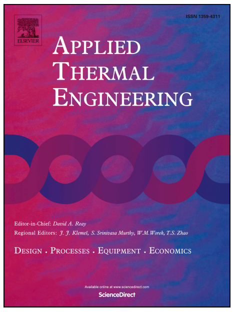

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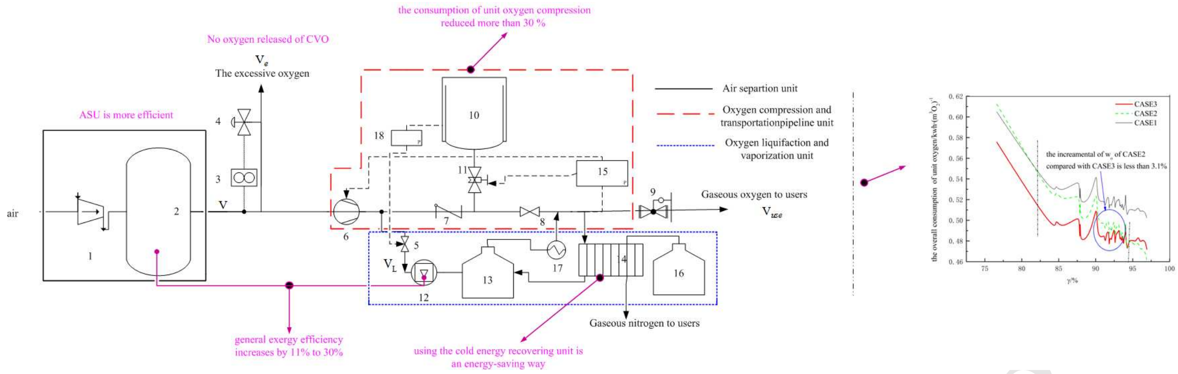
the consumption of unit oxygen compression reduced more than 30 %
No oxygen released of CVO
V_e
The excessive oxygen
ASU is more efficient
Air separtion unit
Oxygen compression and transportationpipeline unit
Oxygen liquifaction and vaporization unit
air
Gaseous oxygen to users
V_{use}
V_L
Gaseous nitrogen to users
general exergy efficiency increases by 11% to 30%
using the cold energy recovering unit is an energy-saving way
the increamental of w_o of CASE2 compared with CASE3 is less than 3.1%
CASE3
CASE2
CASE1
the overall consumption of unit oxygen/kwh·(m^{3}O$_2$)$^{-1}$
γ/%

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Abstract

Generally in the Chinese iron and steel industry, the electricity consumption of cryogenic air separation unit (ASU) is about 14 % of the overall electricity use. To reduce the electricity consumption, the combined variable oxygen (CVO) supply method for ASU is proposed. The exergy calculation program for ASU was developed and the detailed analysis of CVO method was performed. The results show that the general exergy efficiency (GEE) of ASU combined with a liquefaction unit is increased by 11 % to 31 %. The consumption of unit oxygen, the total electricity consumption and the overall consumption of unit oxygen (OCUO) was compared. The OCUO is a suitable method to evaluate the energy-saving potential of CVO. Compared with the load regulation method of Automatic Load Control (ALC), the

OCUO and the unit consumption of compression of CVO reduced more than 4.47 % and 30 %, respectively. It means that CO_2 emission of every reduction 1 % of gaseous oxygen release in a year in Chinese iron and steel industry will contribute approximately 0.75 % to the 2020s CO_2 emission reduction target of China.

Key words: air separation unit; variable load; exergy analysis; energy consumption; CO_2 emission

1 Introduction

Chinese iron and steel industry has become the largest crude steel producer in the world since 1996[1], the iron and steel industry requires quantities of high-purity industrial gas which would be 100 ~ 140 m^3 of O_2 per ton of steel, 100 ~ 140 m^3 of N_2 per of ton steel and 3 ~ 4 m^3 of Ar per ton of steel. For the process of direct reduction iron making, the oxygen demand should be 550 to 650 m^3 per ton of steel [2]. According to a report by World Steel Association in 2013, 779.04 million ton of crude steel in mainland China [3] accounts for 49.23 % of the total production of the whole world. It means that from 7.79 to 10.91 billion m^3 of O_2 is consumed by the Chinese iron and steel industries. The electricity cost of cryogenic air separation unit (ASU) is more than 10 billion US dollars in 2010[4]. The electricity consumption of the iron and steel industry is about 15.2 % of the total electricity consumption in China in 2007 [5], in which the electricity consumption of ASU and the oxygen compression and transportation pipeline (OCTP) unit is about 14 % of the total electricity consumption of iron and steel industries in China[6]. The data is steady in recent years. The net demand for electricity of the industrial gases industry is 31,460 million kilowatt hours (kWh) in the USA in 1998[7]. The demand increased to 39,431 million kWh in 2010, which accounts for 2.8 % of the total electricity purchased by the manufacturing industry and is an increase of 25.4 % compared with the amount in 1998[8]. Due to the high electricity consumption of industrial gases industry, it's meaningful to reduce its electricity consumption by researching new load regulation method of ASU.

Most of the iron and steel industries in China have their own gas production plant in which multiple ASUs operate together to supply whole customers of industry or other customers rather than supply product via pipeline to multiple customers [9]. The gaseous production from ASU is compressed into the OCTP unit to transport to the customers. With large-scale ASU as well as large-scale blast furnaces and converters, the contradiction between supply and demand of gaseous oxygen (GO) has become increasingly prominent because oxygen demand in fluctuation, which causes the oxygen release ratio (ORR, defined as the proportion of the amount of released oxygen product to the oxygen production capacity of ASU) of China to increase. To decrease the ORR in China, three measures were taken. The first is automatic load control (ALC) technique. The second is the variable oxygen (VAROX) supply technique made by the Linde Group [10]. The third is using the liquefaction unit (LU) to liquefy excessive gaseous oxygen (EGO) into a liquid product tank [11~13]. However, the load transition speed of ALC is slow [14, 15] and the ALC should be configured for each ASU. Moreover, load regulation of ALC and VAROX would change the distillation conditions of ASU [16]. In 2010, the average ORR in Chinese large-scale ASUs is more than 3.0 % [11], with an example of Hangzhou Hangyang Co. Ltd which uses ALC as its ORR is 3.75 % [17]. The liquefaction capacity is also limited by the capacity of the liquid product tank. The other countries' gas production plant also consumed large amount of electricity purchased by the manufacturing industry. Therefore, researching new operation strategies to reduce the ORR will result in substantial economic benefits.

For variable load regulation (VLR) of ASU, the load regulation method to change the distillation operation conditions such as ALC is called the internal VLR method. The regulation method to change product flow and pressure in OCTP unit is called the external VLR method. The variable load regulation method combining ALC and LU is called Combine Variable Oxygen (CVO) supply method. This novel method is as follows. Variable load operation of ASU uses ALC, combining liquefaction unit in which the EGO is liquefied by LU or the cold energy recovery (CER) unit using cold from liquid oxygen (LO) or liquid nitrogen (LN) from a storage tank. The exergy analysis of ASU and liquefaction process of CVO is carried out. The electricity consumption of ASU with CVO is compared and evaluated with the electricity consumption of ASU with ALC. It provides guidance for reducing of the electricity consumption of ASU in the next decade.

2 The proposed variable load regulation method

2.1 ALC operation method

Cryogenic air separation is currently the most efficient technology for producing large quantities of oxygen, nitrogen, and argon as gaseous or liquid products [18]. The customer's demand always has fluctuations. Therefore, ASU must rapidly change the product to meet the customers' demand. Otherwise, the EGO has to be released. Today, the EGO is stored into the OCTP unit including oxygen compressor (OC), oxygen pipeline and the storage tank of gaseous oxygen (GO) or LO, whose pressure is maintained at 2.5 to 3.0 MPa. However, the lowest required pressure of GO in steelmaking process is about 1.2 MPa. The important aim to increase the pressure of the oxygen pipeline is for more storage of GO for reducing ORR and balancing between the production and the demand easily. When the demand is larger than the production, the GO in the sphere tank is quickly sent to the customers. Emergency vents must be opened to release GO when the pressure exceeds the upper pressure limits. The electricity consumption of OC could be reduced if we had a quickly load regulation method of ASU.

There are two reasons which cause the gaseous product to release. First, it is far more difficult for ASU to rapidly respond to the changing product to meet the customer demand at the transition speed. The transition speed of ALC is about 4-5minutes per 1 % of rated load. The shorter the transition time of load change, the lesser the energy consumption [15]. Besides, in many manufacturing processes, gaseous product demand is not fixed but intermittent, especially the converter smelting process where oxygen demand lasts 15 minutes while the whole cycle lasts 30 minutes. Secondly, the down-regulation of the load according to the demand of one production may lead to insufficient supply of another gaseous product, because the large-scale ASU is a multi-product production equipment in which the production and purity of one product is related to that of the other products. Moreover, the ASU would be more efficient while it operates under rated load as described by Li [19].

Therefore, load regulation of ASU is necessary not only to take the distillation operation stability of ASU and make the balance between the production and demand for each product of ASU, but also to match the customer demand with the transition speed of load regulation of ASU. With the development of the production technology of iron and steel industry, the ASU has to run under a load condition meeting the increasing demand for GN and argon (Ar). At such load condition, more GO could not be consumed leading to more EGO being released. With oxygen supply system as an example, the CVO is analyzed.

2.2 CVO regulation method

Fig.1 shows the principle of oxygen system of ASU with CVO, which consists of ASU, OCTP unit, and oxygen liquefaction and vaporization unit. The product load rate γ is defined as Eq. (1). The γ means the load rate of oxygen production in this paper unless specified otherwise.

$$\gamma=\frac{V}{V_n}\times 100\% \tag{1}$$

The CVO system has two operational modes to meet the customer's demand:

(1) The internal VLP method for ASU: the γ is increased closely to 100% (described as section 4.1). Then, the ASU operates steadily at some constant γ, until a substantial reduction of the gaseous oxygen demand lasts for more than 4 hours (such as the annual repair of the blast furnace).

(2) The external VLP method for OCTP unit and oxygen liquefaction and vaporization unit: The discharge pressure of valve 9 (see in Fig.1) is set as 1.5 MPa and the average pressure of OCTP unit is maintained around 1.5 MPa. At trough hours when the pressure of OCTP unit is greater than (1.5+Δp) MPa, the EGO is pressurized first by an oxygen compressor and then is liquefied by the LU 12 and CER unit 14 to store in the liquid tank 13. At peak hours, the oxygen demand increases while the production of ASU is not enough, the GO is taken from sphere tank 10 or LO evaporator 14. The principle of operation of CER unit is making the liquid product exchange heat with gaseous product so that the cold energy in the liquid product could be recovered. The Δp is influenced by the capacity of OCTP unit. The volume of the EGO to be liquefied is shown as Eq. (2).

$$V_l = V_e = V - V_{use} \tag{2}$$

In the circumstances described in (1), the down-regulation of load is carried out in ASU by ALC, and the EGO is liquefied into liquid storage tank by oxygen liquefaction and vaporization unit consisting of LU, CER, liquid tank and LO evaporator.

With the increase in γ of ASU, the amount of GO product would also raise so that the instantaneous larger GO demand in steelmaking process could be met. Besides, the EGO could be liquefied into a liquid tank by the oxygen liquefaction and vaporization unit, stopping oxygen from being released; When the GO demand becomes larger, the LO could be evaporated to users. Thus, with increased production and storage of GO, the contradiction between continuous production of ASU and fluctuant demand of users can be solved.

The LU of CVO, shown as Fig.2 (a), is used to liquefy the EGO. The low-pressure nitrogen from ASU, mixed with the nitrogen out of heat exchanger HE5, is compressed by a nitrogen compressor. Then part of the low-pressure nitrogen goes through the expander ET2 to a low pressure and produces cold energy for HE5. The other part of the low-pressure nitrogen undergoes two stages of booster compressors BC and then is cooled by the water coolers. The nitrogen is cooled by heat exchanger HE5 and HE6. Most of the nitrogen is withdrawn to expander ET3 to a specific temperature; the other part of the nitrogen is cooled by heat exchanger HE7 to be LN. The feed oxygen gas undergoes the heat exchangers HE5, HE6 and HE7 to be liquefied as LO.

The CER unit including liquid product storage tank, plate heat exchanger (HE8) and several throttle valves, shown as Fig.2 (b), was similar to the device in ref. 20 and ref.21. The GO from OCTP system undergoes the heat exchanger E8 and then is liquefied as LO, while the LO from liquid tank is vaporized in HE8 and then is sent to OCTP system.

Switching time from full-liquid nitrogen conditions to full-liquid oxygen conditions is about 10 minutes. Under full liquid oxygen conditions, the maximum oxygen production liquefied from gaseous oxygen is 8,750 $m^3 \cdot h^{-1}$. The liquefaction capacity of the CER unit is 5000 $m^3 \cdot h^{-1}$ and its start-up time is 4 min. Therefore, the oxygen supply can be reduced by 13,750 $m^3 \cdot h^{-1}$ within 10 minutes. For example, if applying the CVO, the transition speeds of eight ASUs with product capacity of 102,000 $m^3 \cdot h^{-1}$ would be 1.35 % of rated load per minute and is twice the transition speed of the ASU with ALC. For example, the pressure of OCTP unit at different time is shown in Fig.3. Fig. 3 shows the fluctuation of the pipeline pressure, which can reflect the change of gaseous oxygen demand. Therefore, the shorter the transition time of load change, the quicker the users' demand is met.

The following summarizes three advantages of the CVO regulation: 1) The ASU is running closely to rated load (detailed analysis shown in section 4.3), thus the efficiency of the ASU is higher. 2) The pressure of OCTP unit runs at lower level to reduce the energy consumption of compression. 3) The EGO is liquefied by the LU and CER unit so that the ORR is lower and the LO production is higher. Moreover, the transition speed of CVO is faster than of ALC described as in section 2.2. However, the total energy consumption may increase because the LU would consume a lot of electricity.

3 Exergy analysis of ASU with CVO regulation method

Based on the exergy analysis, a 40,000 $m^3 \cdot h^{-1}$ of external ASU with CVO regulation method and the liquefaction system have been evaluated and the exergy efficiency of single ASU is compared with the ASU combing LU .

3.1 A TYPICAL EXTERNAL COMPRESSED CRYOGENIC AIR SEPARATION PROCESS

The external ASU studied in this paper uses the principle of two-column separation based on a low- and high-pressure distillation column, shown as Fig. 4[22]. Air is firstly compressed in the main air compressor (AC), and then purified to remove the primary impurities such as H_2O, CO_2, and C_2H_2 via molecular sieves absorbers (MS). Part of the pure air is cooled in the main heat exchanger (MHE1) to saturation temperature and enters the lower column (C1). The others enter a turbocharger; then the air is cooled in HE1 to 164 K and is expanded in an expansion turbine (ET); subsequently, the air enters the upper column (C2). The crude argon column (C701, C702 and C703) is configured in the cold box. The product index is shown in Table 1.

3.2 The exergy efficiency

According to Chinese GB/T 14909-2005, named the technical guides for exergy analysis in energy system, the exergy and the general exergy efficiency [23] is calculated by Eq. (3) and Eq. (4), respectively.

$$E_m(T,p) = \sum x_i E_{m,i}(T,p) + RT_0 \sum x_i \ln \frac{f_i}{f_{i0}} + (1 - \frac{T_0}{T}) \Delta_{mix} H_m \qquad (3)$$

$$\eta_{\text{gen}} = \frac{E_{out}}{E_{in}} = 1 - \frac{I_{\text{int}}}{E_{in}} \tag{4}$$

The exergy balance of ASU is shown as Fig.5 (a). The LU can be under three conditions these are full-LO condition without LN production, full-LN condition without LO production and liquid oxygen-nitrogen condition. The exergy balance of LU under full-LO condition is shown as Fig.5 (b), whose total exergy inputs consist of the exergy in the feed and the electricity consumption while the total exergy outputs consist of the exergy of LO and cold water. Similarly, the exergy balance of LU under full-LN condition is shown as Fig. 5(c), whose total exergy inputs consist of the exergy in the feed and the electricity consumption while the total exergy outputs consist of the exergy of LN and cold water.

The exergy calculation software for oxygen-nitrogen-argon mixed working fluid based on Peng–Robinson equation of state was developed by VC ++ 6.0 [24].

The general exergy efficiency (GEE) of ASU and LU is shown in Table 2 and Table 3. The GEE of ASU combined with LU under full-LO condition and full-LN condition is 26.33 % and 31.23 % respectively, which is 1.11 times and 1.31 times of than that of single ASU respectively. It indicates that the process of ASU with LU would be more efficient.

4 Energy analysis of the CVO regulation method

Exergy is the useful analysis method of an amount of energy that can be equally converted into work. Exergy analysis can be used to indicate thermodynamic efficiency of a process, including all quality losses of materials and energies. While an energy analysis of a system is able to evaluate the energy consumption of the proposed strategy. The energy analysis for air separation unit, OCTP unit and oxygen liquefaction and vaporization unit is carried out in this section.

4.1 the energy analysis of the air separation unit

The electricity consumption of ASU varies with γ. Based on JBT 8693-1998, named standard for large and medium scale air separation unit; the consumption of unit oxygen (CUO) is calculated by Eq. (5). The CUO represents the electricity consumption of one m^3 of GO.

$$w_{O_2} = \frac{W_{ASU}}{V_1 + 3\sum V_{lj}} \tag{5}$$

where W_{ASU} is the total electricity consumption for ASU production, including the electricity of the main air compressor, auxiliary device and workshop.

To find effects of various γ on the electricity consumption of ASU, the CUO is calculated. Based on the actual operation data of the 40,000 $m^3 \cdot h^{-1}$ ASU, the result is shown in Fig. 6. The principle of selecting such data is as follows:

1) Ignoring the energy consumption of air pre-purification system; 2) Ignoring the effect of liquid product; 3) Based on the data including inlet airflow, gaseous oxygen flow and gaseous oxygen flow at rated load, both the inlet air flow and gaseous product flow changes in the same proportion, according to ref. [25].

The CUO has dramatic changes with various γ. With increasing the γ, the CUO reduces gradually until γ is equal to 100 %. Then the unit consumption of ASU begins to increase if the γ continues to increase. The ranges of the unit consumption of ASU with different γ is from 0.459 to 0.425 kW·h ·$(m^3O_2)^{-1}$. The CUO with γ of 80 % increases by 5.99 % compared to the one with γ under rated load condition. The effect of the load regulation process on the CUO is significant. It means that the appropriate load regulation method can save energy.

4.2 The electricity analysis of the oxygen compression and transportation pipeline unit

Thus the electricity consumption of OCTP unit would induce further if the pressure of it decreases to 1.5 MPa as described in section 2.1. The electricity consumption of OC in OCTP unit is calculated by Eq. (6) [26]. Part of the compressibility factor *A* calculated by the program developed in section 3.2 is listed in Table 4.

$$w_{com} = \frac{1}{\mu}\frac{k}{k-1}AR_mT\left[\left(\frac{p_{out}}{p_{in}}\right)^{\frac{k-1}{k}} - 1\right] \qquad (6)$$

Ignoring the exergy of cold water and the exergy loss of the compressed oxygen into the OCTP unit, the exergy analysis of the OC in OCTP unit is carried out. Its exergy inputs include the exergy of inlet oxygen and electricity consumption feeding to the OC and its exergy outputs include the exergy of outlet oxygen.

Fig. 7 shows the effect of different discharge pressures of oxygen/nitrogen compressors on the electricity consumption, general exergy efficiency and exergy loss of that. In Fig. 7 (a), with the discharge pressure of the OC decreasing from 3.04MPa to 1.5MPa, the electricity consumption and exergy loss of the OC reduces 30.22% and

38.38% respectively, while its general exergy efficiency increases from 59.67% to 67.33%. Thus in order to save electricity, it is very necessary to decrease the pressure of OCTP unit. Similarly, the electricity consumption, general exergy efficiency and exergy loss of the nitrogen compressor at different discharge pressure are shown in Fig. 7 (b).

4.3 Comparison of three evaluation methods at different load regulation methods

The total electricity consumption includes that of ASU, the OCTP unit and oxygen liquefaction and vaporization unit. The total electricity consumption on three cases is compared. For CASE 1, the ALC is used on ASU as described section 2.1. For CASE 2 and CASE 3, the CVO is applied on ASU. The γ in CASE 2 raised only 5 % than before while the γ in CASE 3 increases to 100 %. The γ is made equal to 100 % in the above comparison process especially when the (γ +5 %) is larger than 100 %. Moreover, it is assumed that there is enough space for liquid storage tanks.

The total electricity on CASE 1, CASE2 and CASE3 is calculated by Eq. (7), Eq. (8) and Eq. (9) respectively. Where V_{CASE1} is the production of ASU in CASE 1; V_{use} is the user's demand; V_l is the EGO to be liquefied; w, w_{com} and w_l is the consumption of unit oxygen, the consumption of unit oxygen compression and the consumption of unit oxygen liquefaction respectively. The $V_{CASE1} \cdot w$, $V_{use} \cdot w_{com}$ and $V_l \cdot w_l$ in Eq. (7) represent the CUO, the electricity of OCTP unit and the electricity of oxygen liquefaction and vaporization unit.

$$W_{CASE1} = V_{CASE1} \cdot w + V_{use} \cdot w_{com} + V_l \cdot w_l \quad (7)$$

$$W_{CASE2} = V_{CASE2} \cdot w + V_{\text{use},CASE2} \cdot w_{\text{com}} + (V_{CASE2} - V_{\text{use},CASE2}) \cdot w_{L} \qquad (8)$$

$$W_{CASE3} = V_{CASE3} \cdot w + V_{\text{use},CASE3} \cdot w_{\text{com}} + (V_{CASE3} - V_{\text{use},CASE3}) \cdot w_{L} \qquad (9)$$

The consumption of unit oxygen, calculated by Eq. (10), is fitted by the data derived from Fig.6. The consumption of unit oxygen compression is obtained by Eq.(6) . The consumption of unit oxygen liquefaction is achieved from the actual data. When 8,750 $m^3 \cdot h^{-1}$ of oxygen is liquefied, the electricity consumption of LU is 4, 956.52 $kW \cdot h \cdot h^{-1}$, thus the consumption of unit oxygen liquefaction is 0.57 $kW \cdot h \cdot m^{-3} O_2$.

$$w = 0.44277 + \frac{-0.8353}{(18.83801 \times \sqrt{\pi / 2})} \times e^{(-2 \times ((v - 98.99815)/18.83801)^2)} \qquad (10)$$

The daily data of supply and demand as well as liquefaction and release of oxygen during 59 days in 2009 is shown in Fig.8. The V is always beyond V_{use}. As the data in Fig.8 is randomly selected, the results could be used to analyze other days of the year 2009.

The effect of γ on the total electricity consumption on the three cases (CASE 1, CASE 2 and CASE 3) is shown in Fig. 9. The increase of γ suggests an increase of the total energy consumption of CASE 1 and CASE 3 as well as the gradual reduction of the total energy consumption of CASE 2. When γ varies from 84 % to 95 %, The descending order of the electricity consumption on the three cases is CASE 2, CASE 3 and CASE 1, but the electricity consumption on CASE3 is closer to that on CASE 1. While γ is greater than 95 %, the electricity consumption of CASE 2 is the lowest among the three cases. It means that the total electricity consumption is influenced by the γ. For several points in Fig.9, for example γ is equal to 76 %, 87 % and 90 %; the value of V_0/V_{use} is greater 1.04. Thus, it can be referred that the EGO should be released rather than be liquefied if the value of V_0/V_{use} is greater than 1.04.

The electricity consumption of CASE 2 is the lowest among the three cases while γ is greater than 95 %, hence the CASE 2 should be studied further by applying CER. The amount of EGO liquefied by CER is V_r. The medium pressure nitrogen (MN) is liquefied by LO to be LN which is used to liquefy the EGO.

Fig.10 shows a flow diagram of the cold energy recovering unit in Aspen Plus. Where, (a) represents that 1 $kmol \cdot h^{-1}$ EGO is liquefied by LN and (b) represents that 1 $kmol \cdot h^{-1}$ MN is liquefied by LO. Table 5 shows the simulation conditions of CER process.

The simulation results show that liquefying 1 $kmol \cdot h^{-1}$ EGO need about 0.89 $kmol \cdot h^{-1}$LN, which means that the ratio of EGO and LN is 1:0.89; Liquefying 1 $kmol \cdot h^{-1}$ MN need about 1.6 $kmol \cdot h^{-1}$LO, which means that the ratio of LO and MN is 1.6:1. Such ratio would not change until the temperature and pressure of product in table 5 changed.

The energy consumption of CER unit consists of the electricity consumption of MN compression and the cold loss of liquid product exchanging heat with gaseous product.

The electricity consumption of MN compression is calculated by Eq. (11).

$$W_N = V_r \cdot 0.896 \cdot w_N \tag{11}$$

where W_N is the electricity consumption of MN compression; the w_N is the unit consumption of nitrogen compression, shown as Fig.7 (b).

The cold loss is calculated by Eq. (12).

$$Q = V \cdot c_p \cdot \Delta t \tag{12}$$

where Q is cold loss; c_p is heat capacity at constant pressure; Δt is the temperature difference at warm end of CER unit.

Based on the conditions in table 5, the total energy consumption can be calculated by Eq. (13).

$$W_r = V_r \cdot 0.896 \cdot w_N + \frac{V_r \cdot 0.94239 \cdot \Delta t_O}{3600} + \frac{V_r \cdot 1.0482 \cdot \Delta t_N}{1.6 \times 3600} \tag{13}$$

If the CER is not applied, the EGO would be released. The electricity due to the EGO released is calculated by Eq. (14).

$$W_e = V_r \cdot w \tag{14}$$

where W_e is the electricity of EGO released; w is the unit consumption of oxygen, shown as Fig. 6.

The difference of energy consumption between CER unit and EGO released is set as ΔW. Fig. 11 shows the effect of V_r on such difference of energy consumption. It indicates that if the ASU operates stable, W_r is always smaller than W_e, which means that the total energy consumption of CER unit would decrease with increasing V_r. Thus, applying the CER unit is an energy-saving measure.

The CUO is selected to evaluate the electricity consumption of various methods. Table 6 lists the average of the CUO of the above three cases during 59 days in Fig. 8.

Regardless of electricity consumption of liquefaction, the CUO of CASE 2 and CASE 3 compared to CASE 1 reduce by 2.73 % and 1.82 % respectively, and the unit consumption of oxygen compression decreases by 30 %.

Table 6 also reveals that the unit consumption of oxygen liquefaction is greater than of ASU and compression, which means that the electricity consumption of OCTP unit would increase because of using LU.

To evaluate the actual energy-saving potential of CVO method further, the overall consumption of unit oxygen (OCUO) is selected. The OCUO is defined as the ratio of the total electricity consumption and the actual amount of gaseous product V_i including the gaseous product consumed and stored but not including the released gases. The OCUO is calculated as Eq. (15) [27]. The other product capacities of a multi-product production ASU should be converted into oxygen product capacity, the converted factor can be obtained by the minimum separation work of each component calculated by Eq. (16)[27].

Here i=1, 2 and 3 respects O, N and Ar, respectively

$$\mathrm{w}_O = \frac{W_{tol}}{\sum \alpha_i V_i + 3\sum V_{Lj}} \tag{15}$$

$$N = nRT\sum \mathrm{y}_i \ln\frac{1}{\mathrm{y}_i} \tag{16}$$

It is assumed that air consists of O, N and Ar where the mole fraction of them is 20.95%, 78.12% and 0.93% respectively. The minimum separation work of one mole of air to be separated is 62.4 kJ ·(m^{3}air)$^{-1}$.

Thus the minimum separation work of oxygen is:

$N_1 = N/y_1 = 297.80$ kJ ·(m^{3}O$_2$)$^{-1}$

And the minimum separation work of argon is:

$N_2 = N/y_2 = 6708.60$ kJ ·(m^{3}Ar)$^{-1}$

So, $\alpha_O = 1, \alpha_{Ar} = 22.527, \alpha_N = 0.026826$.

Fig. 12 shows the influence of γ on the w_O on the three cases. An increase of γ shows a reduction of the w_O. The w_O under CASE 3 and CASE 2 reduces 6.22% and 4.48% compared to CASE 1 respectively. When the γ is bigger than 95 %, the w_O under CASE 3 is greater than under CASE 2, consistent with the releations of total energy shown in Fig.9. When the γ varies between 90 % and 95 %, the w_O under CASE 3 gets the minimum, and the incremental of w_o under CASE 2 compared with CASE 3 is less than 3.1%. The reason for decreasing the w_O is that the V_i increases, which is achieved by liquefying the EGO without oxygen released. However, the total electricity consumption increases due to the liquefying process. When the γ is more than 95%, the w_O under CASE 2 is minimal within the lowest total elecrictiy consumption, because the whole EGO is liquefied rather than released.

To sum up, the CVO regulation method is influenced by γ. The CVO regulation method is modified based on the actual conditions as follow. When the ratio of V_0 to V_{use} is less than 1.04 and the product rate is greater than 95 %, the ASU system should operate under rated load condition. While the γ varies from 85 % to 95 %, the γ should be increased by 5 %. If γ is less than 85 %, the ALC should be applied to ASU system.

While the ratio of V_0 to V_{use} is more than 1.04, keeping V_0 constant, the EGO should be released. For example, after applying the CVO regulation method, an ASU system whose production is 82,000 m^3/h and its OCTP unit in particular, achieves 1.25 million kWh electricity-saving due to the EGO being liquefied rather than be released.

In China, the total oxygen consumption is about 10.91 billion m^3 of O_2 while the unit consumption of oxygen is assumed to be 0.42 kWh $\cdot(m^3 \cdot O_2)^{-1}$ in 2013. If the oxygen release ratio decreases by every 1 % of the above oxygen consumption, the electricity-saving would be 4.58×10^{10} kWh for ASU system. As the CO_2 emission of unit electricity generated by coal-fired power generation system is 1.03 kg/kWh [28], the CO_2 emissions could reduce 5.28×10^{7} tons at least annually with the above energy-saving. China promised to reduce the CO_2 intensity by 40-45 % by 2020 from 2005 levels, and China's CO_2 emission reduction must exceed 6994.9 [29] million tons to fulfill the promised CO_2 emission reduction target of China in 2020. It can be inferred that the CO_2 emission reduction of iron and steel industry contributes 0.67 % to China's CO_2 emission reduction in 2020 if the oxygen releasing rate decreases by every 1 % of gaseous oxygen consumption in 2013.

5 Conclusion

Aiming at achieving energy savings and reducing oxygen release ratio, the exergy calculation program was devoloped. Besides, the unit consumption of oxygen, the total energy consumption and the overall unit consumption of oxygen were selected to determine energy-saving of different load regulation method. After that, the CVO regulation method is proposed for ASU

Compared with the current regulation method, the CVO regulation strategy presented in the paper has following features.

(1) The contradiction between continuous production of ASU and fluctuant demand of users can be solved, because of increase of production and storage of gaseous oxygen.

(2) The transition speed of CVO regulation method is about 3.125 %/min twice as the transition speed of current regulation method.

(3) The general exergy efficiency of ASU combining with liquefaction unit is increased by 11 % to 31 %. The OCUO is suitable method to evaluate the energy-saving potential of CVO. The OCUO and the unit consumption of compression of CVO reduced more than 4.47 % and 30 %, respectively. Besides, using the cold energy recovering unit is an energy-saving way.

(4) The proposed regulation method is related to product load rate. While the product load rate is more than 95 %, the ASU operates under rated load and the CVO regulation method is energy-saving.

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Nomenclature			
A	coefficient of compressibility (-)	**Superscript**	
c_p	heat capacity at constant pressure($kJ·m^{-3}·℃^{-1}$)	*0*	reference conditions of enthalpy
E	exergy (kW)	*o*	the liquefaction unit running under full-liquid oxygen condition
f	fugacity (Pa)	*n*	the liquefaction unit running under full-liquid nitrogen condition
H	specific enthalpy ($J·mol^{-1}$)	**Subscript**	
I	exergy loss (kW)	*ASU*	air separation unit system
k	adiabatic compressibility(-)	*CASE*	three cases analyzed in the paper
N	the minimum separation work （$kJ·m^{-3}$）	*CVO*	combined variable oxygen method
n	molar (mol)	*com*	compressor
p	pressure (Pa)	*e*	the excess gaseous oxygen
Q	cold loss ($kJ·h^{-1}$)	*gen*	general exergy efficiency
R	molar gas constant ($J·K^{-1}·mol^{-1}$), 8.3143 $J·K^{-1}·mol^{-1}$	*i*	component i
T	temperature (K)	*in*	inlet flow
V	oxygen product volume (m^3)	*j*	component j
W	electricity consumption (kW)	*l*	liquid product
x	molar fraction	*n*	the product flow under rated load
Greek Letters		*O*	oxygen
α	coefficient of conversion(-)	O_2	gaseous oxygen
γ	product rate (%)	*r*	cold energy recovering unit
η	general exergy efficiency (%)	*0*	ambient reference conditions
μ	efficiency of compressor (%)	*use*	user's demand of oxygen product

References

[1] He F, Zhang Q, Lei J, et al. Energy efficiency and productivity change of China's iron and steel industry: Accounting for undesirable outputs [J]. Energy Policy, 2013, 54: 204-213.

[2] Guilin. Chen. Configuration of air separation unit for steelworks. Gas separation, 2005, (1): 004. (in Chinese)

[3] The crude steel production of 2012 from WORDSTEEL ASSOCIATION. Available at: http://www.worldsteel.org/zh/statistics/statistics-archive/2013-steel-production.html, 08-04-2014.

[4] Zhongzhou Chen, Michael A. Henson, Senior Member, IEEE, Paul Belanger, and Lawrence

Megan. Nonlinear model predictive control of high purity distillation columns for cryogenic air separation [J]. Control Systems Technology, IEEE Transactions on, 2010, 18(4): 811-821.

[5] Z.C. Guo, Z.X. Fu. Current situation of energy consumption and measures taken for energy saving in the iron and steel industry in China [J]. Energy, 2010, 35 (11): 4356-4360.

[6] Lige Tong, Li Wang, Yanping Zhang, Huazhi Li. The oxygen utilization decision support system and operation simulation system for air separation units [J]. Iron and Steel (Beijing), 2003, 38(3): 53-56.(in Chinese)

[7] Karwan MH, Keblis M. Operations planning with real time pricing of a primary input. Computers & Operation Research. 2007, 34(3): 848-867.

[8] Energy information association. Manufacturing energy consumption survey. Available at: http://www.eia.doe.gov/consumption/manufacturing/data/2010/#r1.html, 019-09-2014.

[9] Vinson D R. Air separation control technology [J]. Computers & Chemical Engineering, 2006, 30(10): 1436-1446.

[10] Xueshen Yang. 50000m^3/h air separation plant employing quick variable-load model made by Linde. Cryogenic Technology, 2003,(4): 22-25.(in Chinese)

[11] Jianqing Chen. Baosteel's practice of reducing the oxygen emission rate [J]. Energy for Metallurgical Industry, 2012, 31(3): 9-10.(in Chinese)

[12] Chenglong Li. Analysis of the operation to balance the oxygen supply-demand pipeline net [J]. Cryogenic Technology, 2012, (3): 10-12. (in Chinese)

[13] Luanfeng Zhai, Wenqiang Lin. Summary on measures for reducing oxygen bleeding from air separation unit at steel enterprises [J]. Cryogenic Technology, 2008, (3): 61-63. (in Chinese)

[14] Junfen Liu. Automatic load control technique for air separation plants [J]. Cryogenic Technology. 2002, (4): 14-16. (in Chinese)

[15] B.Roffel, B.H.LBetleln, J.A.EdeRuijter. First principles dynamic modeling and multivariable control of a cryogenic distillation process [J]. Computer & Chemical Engineering, 2000, 24: 111-123.

[16] Lvnan Fu, Chengan Wu. Feasibility analysis of the application of interchange of LO_2 and LN_2 to 10000m^3/h air separation unit [J]. Cryogenic Technology, 2003, (4): 9-14. (in Chinese)

[17] Xu Z, Zhao J, Chen X, et al. Automatic load change system of cryogenic air separation process [J]. Separation and Purification Technology, 2011, 81(3): 451-465.

[18] R.L Cornelissen, G.G Hirs. Exergy analysis of cryogenic air separation [J]. Energy Conversion and Management, 1998, 39(16): 1821-1826.

[19] Huazhi Li, Lige Tong, Ting Gao. Economic operation analysis on modern air separation unit: Part II--Production with multi-product [J]. Gases Separation, 2012, (5): 19-24. (in Chinese)

[20] Enwei Sun, Changhong Sun. Technique involving recovering the refrigeration capacity of liquid argon [J]. Cryogenic Technology, 2002, (5): 13-15. (in Chinese)

[21] Bernd Ameel, Christophe T'Joen, Kathleen De Kerpel, Peter De Jaeger, Henk Huisseune, Marnix Van Belleghem, Michel De Paepe. Thermodynamic analysis of energy storage with a liquid air Rankine cycle [J]. Applied Thermal Engineering, 2013, 52(1):130-140.

[22] Hualing Fu, Xinzhong, Shumei Cai, Jianmin Ning. Configuration and summarization of operation of two sets of 40000m^3/h air separation plant of Bayi Iron & Steel [J]. Cryogenic Technology, 2012, (2): 17-20. (in Chinese)

[23] L.V. Van der Ham. Improving the exergy efficiency of a cryogenic air separation unit as part of an integrated gasification combined cycle [J]. Energy Conversion and Management, 2012, 61: 31-42.

[24] Li Yao, Lige Tong, Yunfei Xie, Jianbiao Shen, Shiqi Li. Exergy Analysis for Air Separation Unit [J]. Industrial Heating, 2013, (2): 22-24. (in Chinese)

[25] Fugen Xu, Jianyu Wan, Li Wang. Analysis and computation of main operating parameters for variable load adjustment of air separation unit [J]. Cryogenic Technology, 2006, (04): 38-46. (in Chinese)

[26] Chunyang Dong, Li Wang, Yanping Zhang. Energy consumption structure of air-separation products in steel plants [J]. Journal of University of Science and Technology Beijing, 2008, 30(11): 1307-1311. (in Chinese)

[27] Huazhi Li. Technology of oxygen production (the second edition) [M]. Beijing: Metallurgical Industry Press, 2009. (in Chinese)

[28] Ping Hou, Hongtao Wang, Hao Zhang, Dong Ci, Na Huang. Greenhouse gas emission factor of Chinese power grids for organization and product carbon footprint [J]. China Environment Science, 2012, 32(6): 961-967. (in Chinese)

[29] Xia Chen, Li Wang, Lige Tong. Energy saving and emission reduction of China’s urban district heating [J]. Energy Policy, 2013, 55: 677-682.

Tables

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Fig.12. The influence of the γ on the overall consumption of unit oxygen

Table 1. The product index of 40, 000 m^3/h of ASU

Product	Production $/m^3 \cdot h^{-1}$	Purity	Pressure /MPa(G)	Temperature/K
Oxygen gas	40,000	99.6 % O_2	0.0191	281.25
Liquid oxygen	1,500	99.6 % O_2	0.17	95.15
Nitrogen gas	40,000	$\leq 3\times10^{-6}$ O_2	0.013	285.75
Liquid nitrogen	500	$\leq 3\times10^{-6}$ O_2	0.32	80.15
Liquid argon	1,360	$\leq 2\times10^{-6}$ O_2, $\leq 2\times10^{-6}$ N_2	0.16	90.15

Table 2. The general exergy efficiency of ASU under rated load condition

Input		Exergy/kW	Output	Exergy/kW
Air in feed		0	Gaseous nitrogen	455.79
Electricity consumption	air compressor	20,600	Liquid nitrogen	121.06
	water pump	400	Gaseous oxygen	2,125.29
	water cooler	182	Liquid oxygen	413.16
	heating unit	456	Liquid argon	485.22
Cooling water in feed		33.28	Crude nitrogen	1,231.36
			Cooling water exiting	334.12
E_{in}		21,671.28	E_{out}	5,166
The GEE (η_{gen})		$E_{out}/E_{in}\times100$ %=23.84 %		

Table 3. The general exergy efficiency of liquefaction unit

Input	Exergy/KW	Output	Exergy/ KW
Electricity consumption of LU	4,956.52	Gaseous nitrogen	22.00
Middle pressure nitrogen	941.29	Liquid nitrogen	3,088.73
Gaseous oxygen in feed	816.86	Liquid oxygen	2,322.18
Cooling water in feed	128.35	Cooling water exiting	374.51
E_{in}^{o}	5,901.73	E_{in}^{o}	2,696.69
E_{in}^{o}	6,026.16	E_{in}^{o}	3,485.24
$_{gen}^{o}$	2,696.69/5,901.73×100 %=46.69 %		
η_{gen}^{o}	3,485.24/6,026.16×100 %=57.84 %		

Note: the superscripts o and n represent the LU running under full-LO condition and full-LN condition respectively.

Table 4. The Compressibility factor A of oxygen

Pressure/MPa	0.5	1.0	1.5	2.0	2.5	3.0
Compressibility factor *A*	0.9977	0.9949	0.9921	0.9982	0.9866	0.9839

Table 5. Simulation conditions of the cold energy recovering unit

		Temperature/K	Pressure/MPa	Volume/(kmo·h^{-1})	Vapor fraction
(a)	MN	293.15	0.5	1	1
	LO	91.15	0.11	-	0
(b)	GO	293.15	1.5	1	1
	LN	80.15	1.371	-	0

Table 6. The average of the consumption of different cases

		w_{O_2} /kW·h·(m^{3}O$_2$)$^{-1}$	w_{com} /kW·h·(m^{3}O$_2$)$^{-1}$	w_l /kW·h·(m^{3}O$_2$)$^{-1}$
CASE1		0.439	0.200	0.566
CVO	CASE2	0.427	0.140	0.566
	CASE3	0.431	0.140	0.566

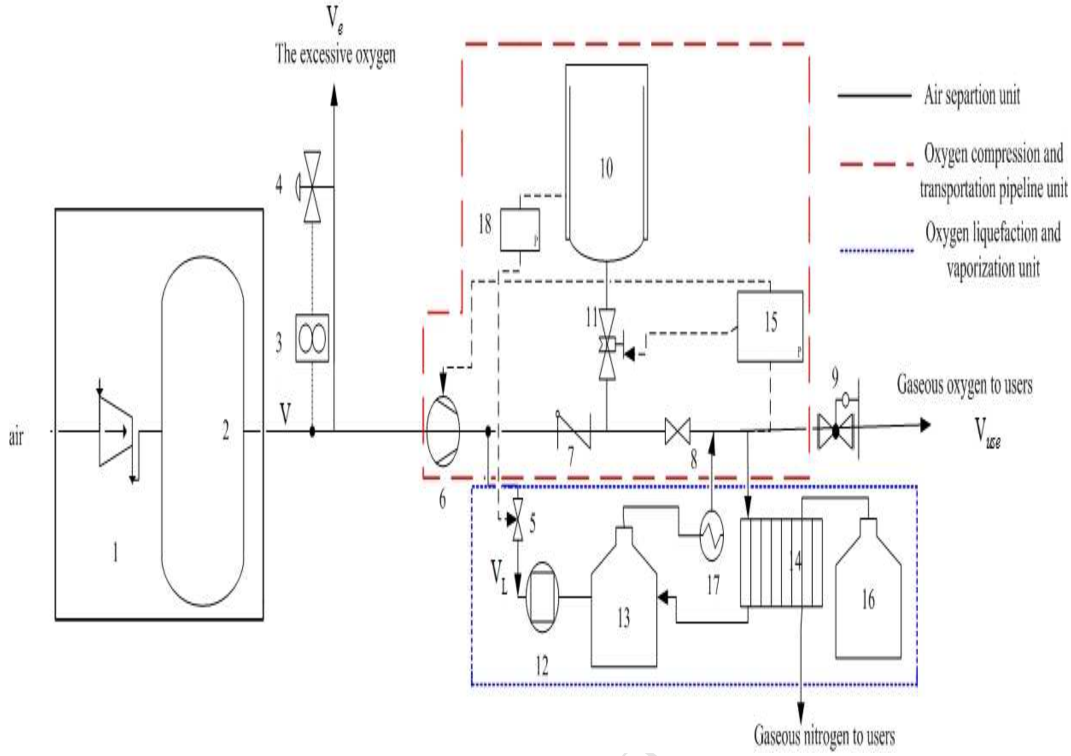

Fig. 1. Principle of oxygen system of ASU with CVO

1-air compressor; 2- distillation column; 3- flowmeter; 4- bleed valves; 5, 8-valve; 6-oxygen compressor; 7-oxygen check valve; 9- reducing valve of user; 10-spherical tank; 11- pressure control valve; 12- liquefaction unit; 13-liquid oxygen tank; 14- cold energy recovering unit; 15, 18-pressure sensor; 16-liquid nitrogen tank; 17- liquid oxygen evaporator;

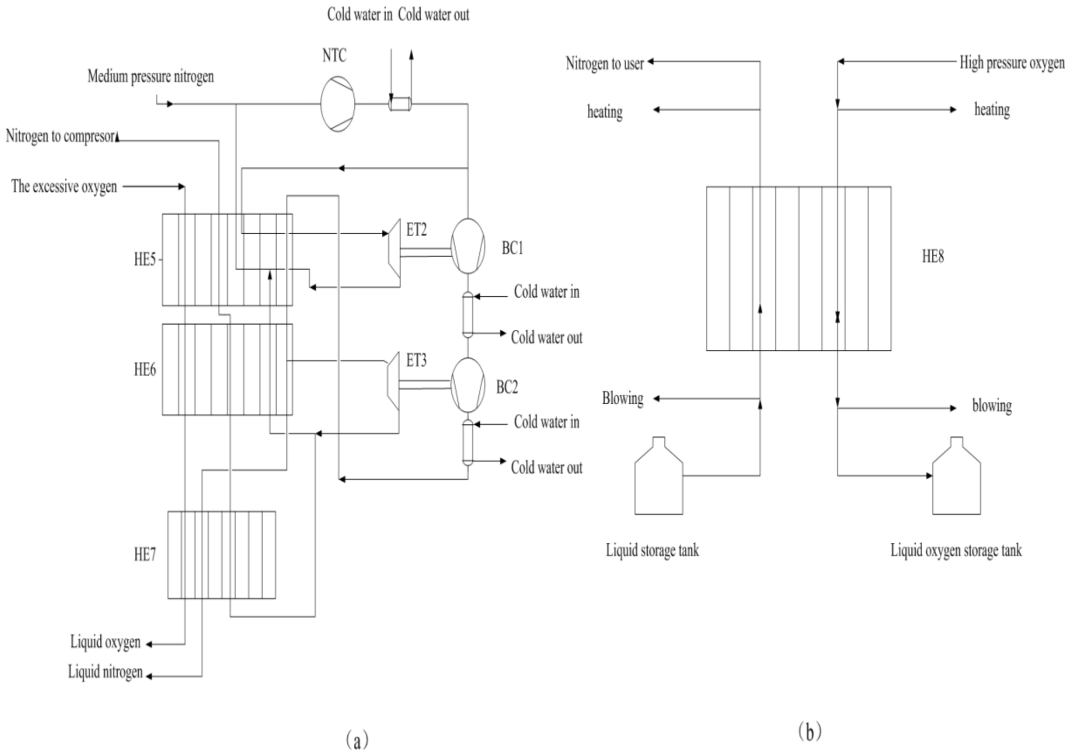

Fig. 2. Diagram of the liquefaction unit and the cold energy recovering unit

NTC—nitrogen compressor; BC—booster compressor; ET—expansion turbine; HE—heat exchanger

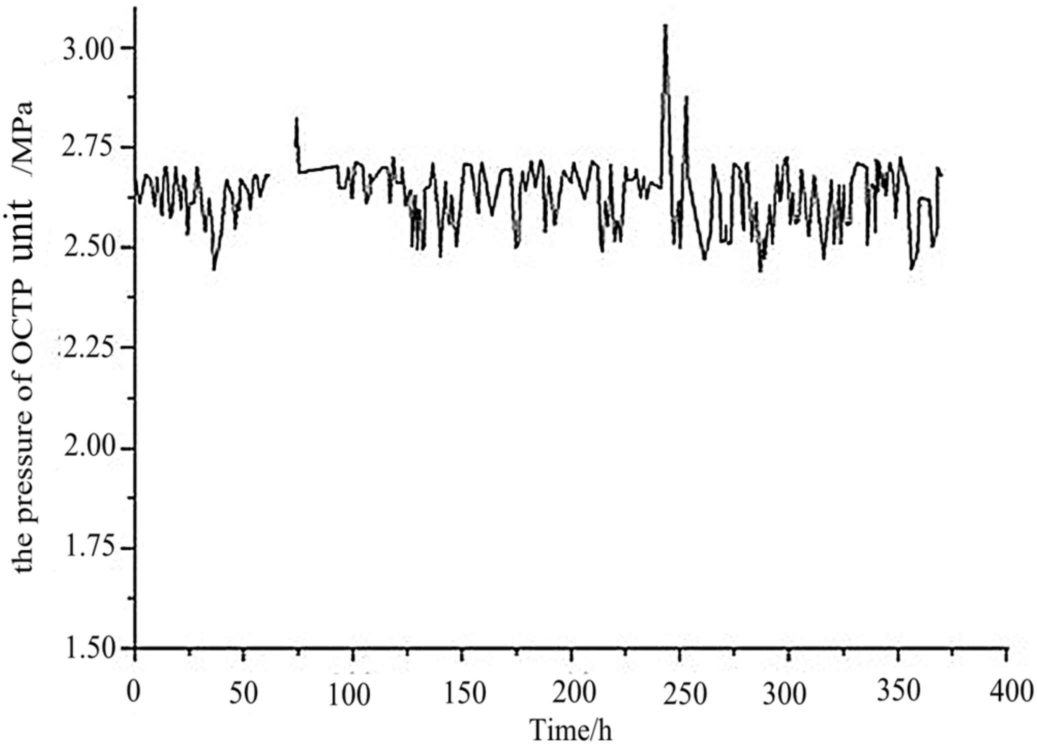

Fig. 3. The pressure of oxygen compression and transportation pipeline unit

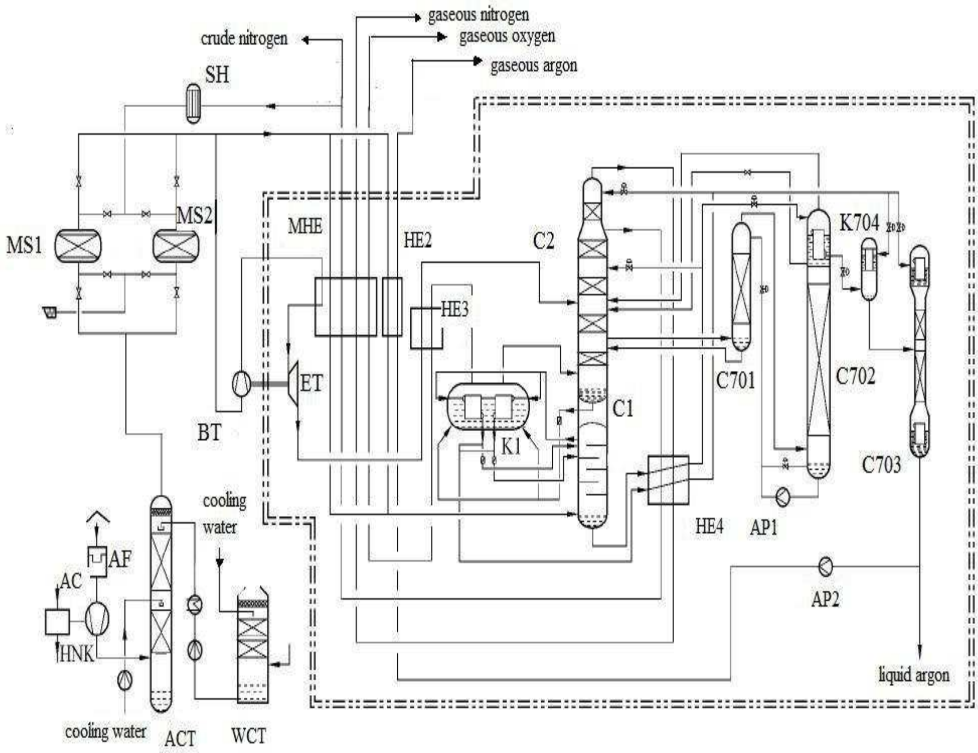

Fig. 4. Diagram of the typical externally compressed cryogenic air separation process

AF—air filter; AC—air compressor; ACT—air cooling tower; WCT—water cooling tower; MS—molecular sieve purifier; SH—steam heater; BT—booster turbine; ET—expand turbine; MHE—main heat exchanger; HE2—heat exchanger of argon; HE3—expand air sub-cooler; E4—liquid sub-cooler; K1—main cooling evaporator; C1—lower column; C2—upper column; C701—crude argon column I; C702—crude argon column II; C703—pure argon column; K704—Crude argon liquefier; AP—argon pump

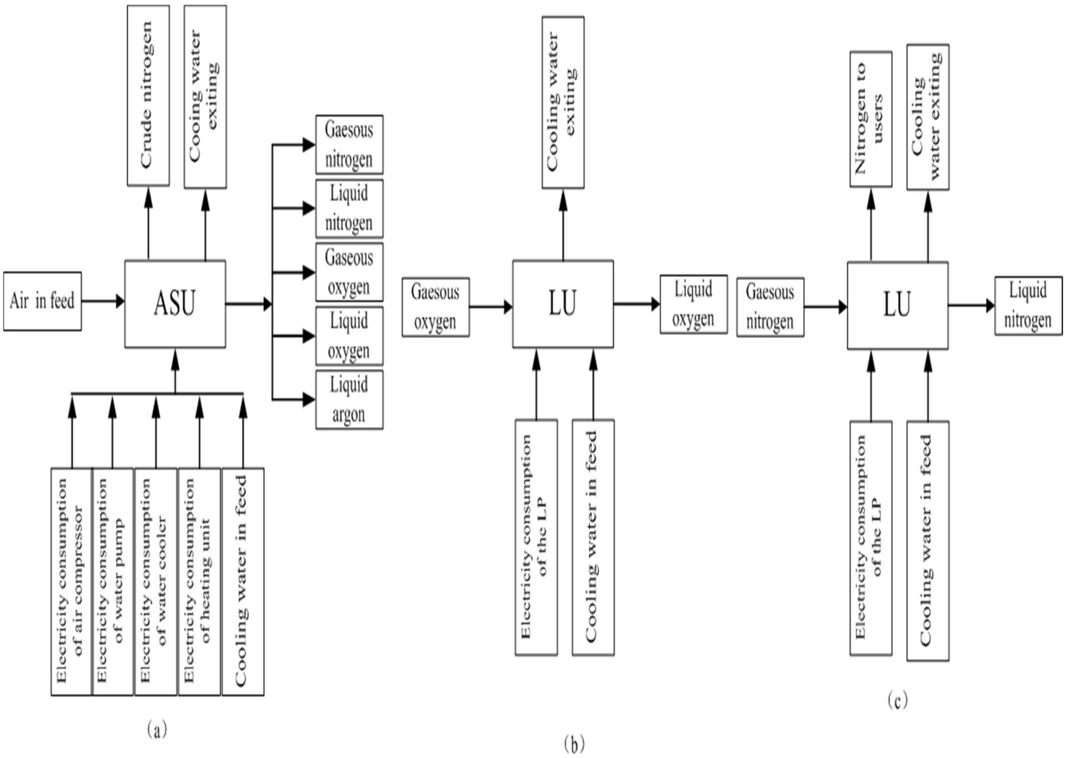

Fig. 5. The exergy balance of ASU and LU

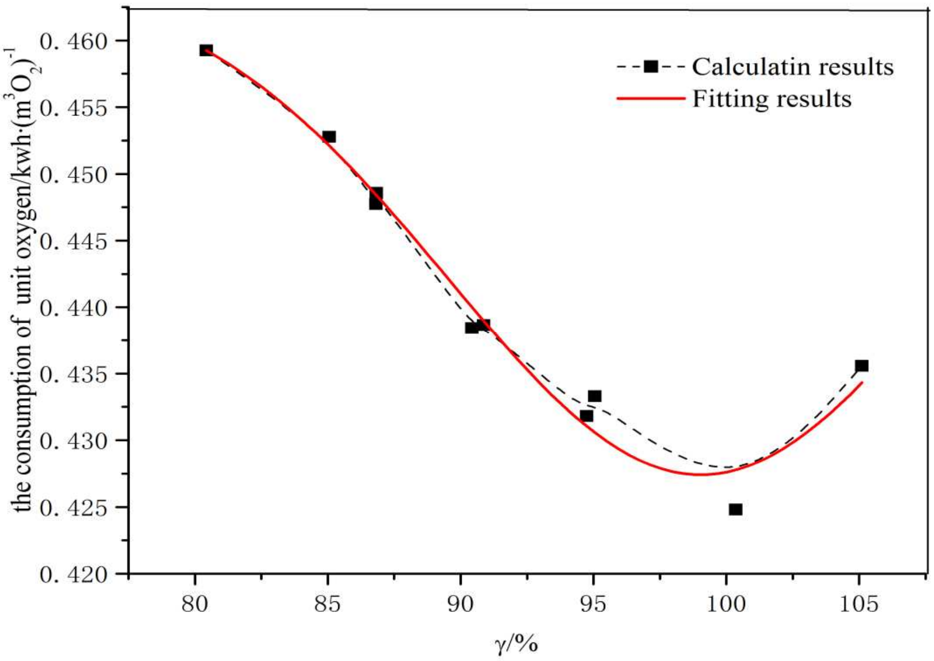

Fig. 6. The effect of γ on the consumption of unit oxygen

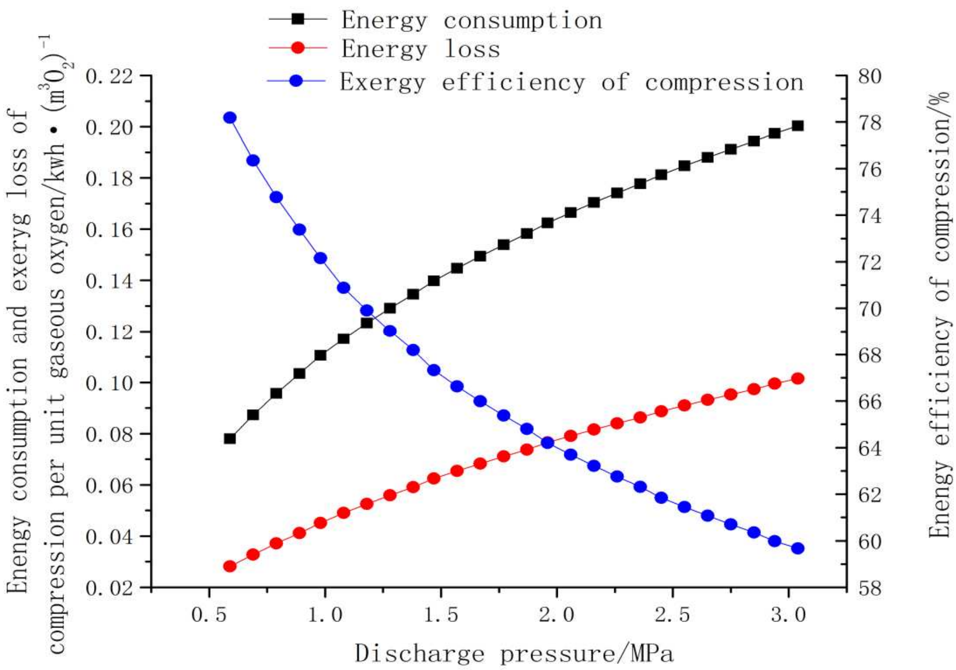

Fig. 7(a). The effect of different discharge pressure of oxygen compressor on the energy consumption, exergy efficient and exergy loss of it

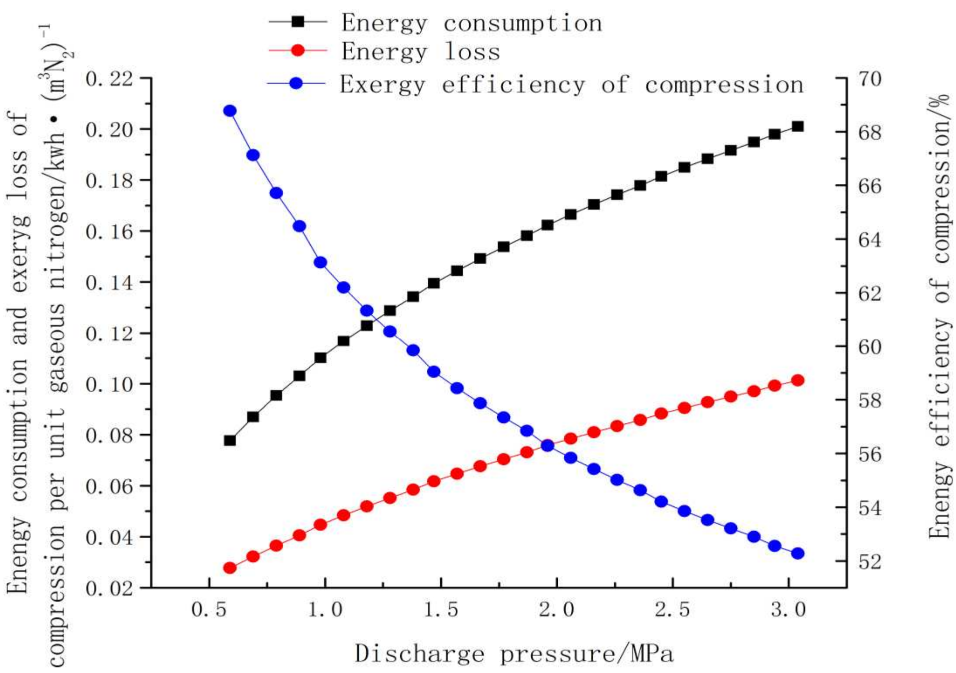

Fig. 7(b). The effect of different discharge pressure of nitrogen compressor on the energy consumption, exergy efficient and exergy loss of it

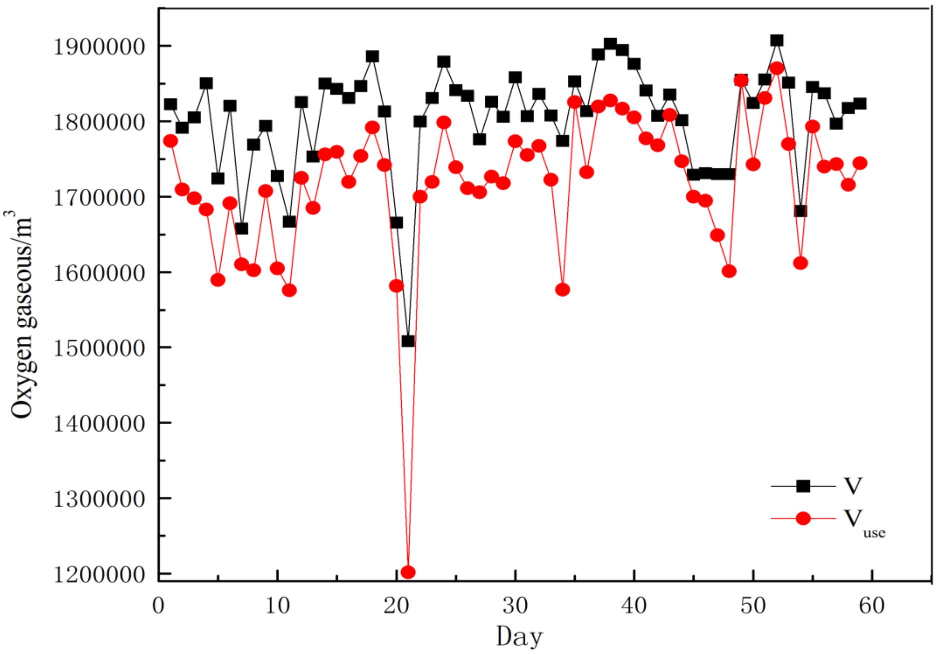

Fig. 8(a). Daily data of supply and demand of oxygen during 59 days in 2009

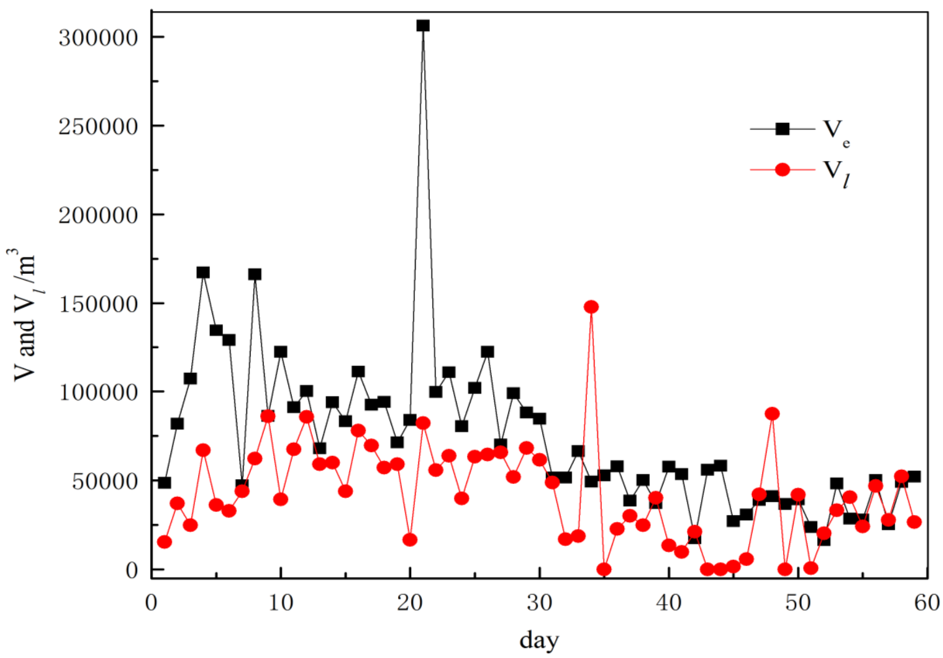

Fig. 8(b). Daily data of liquefaction and release of oxygen during 59 days in 2009

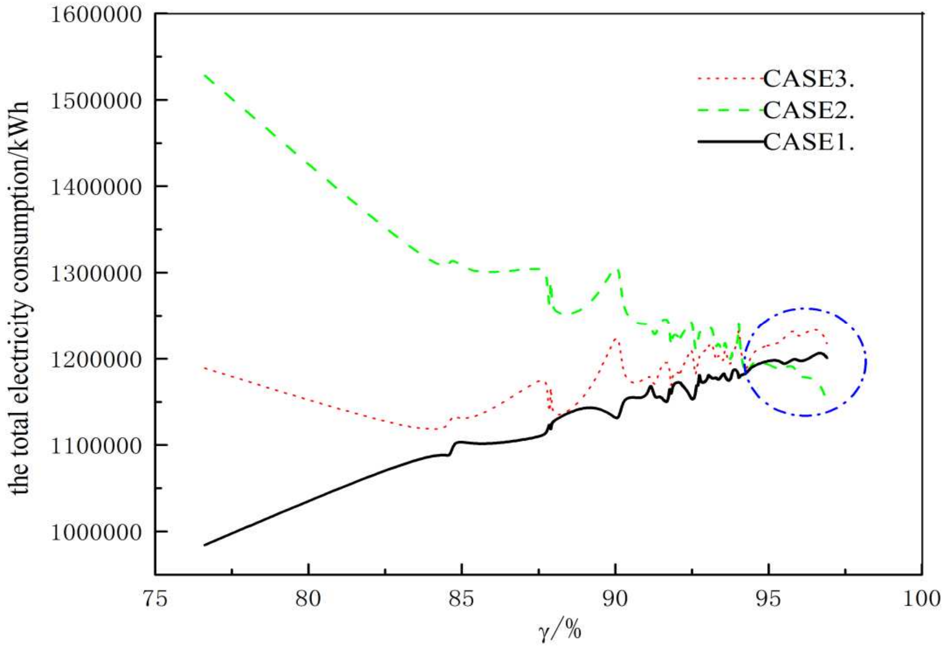

Fig. 9. The effect of γ on the total energy consumption of the three cases

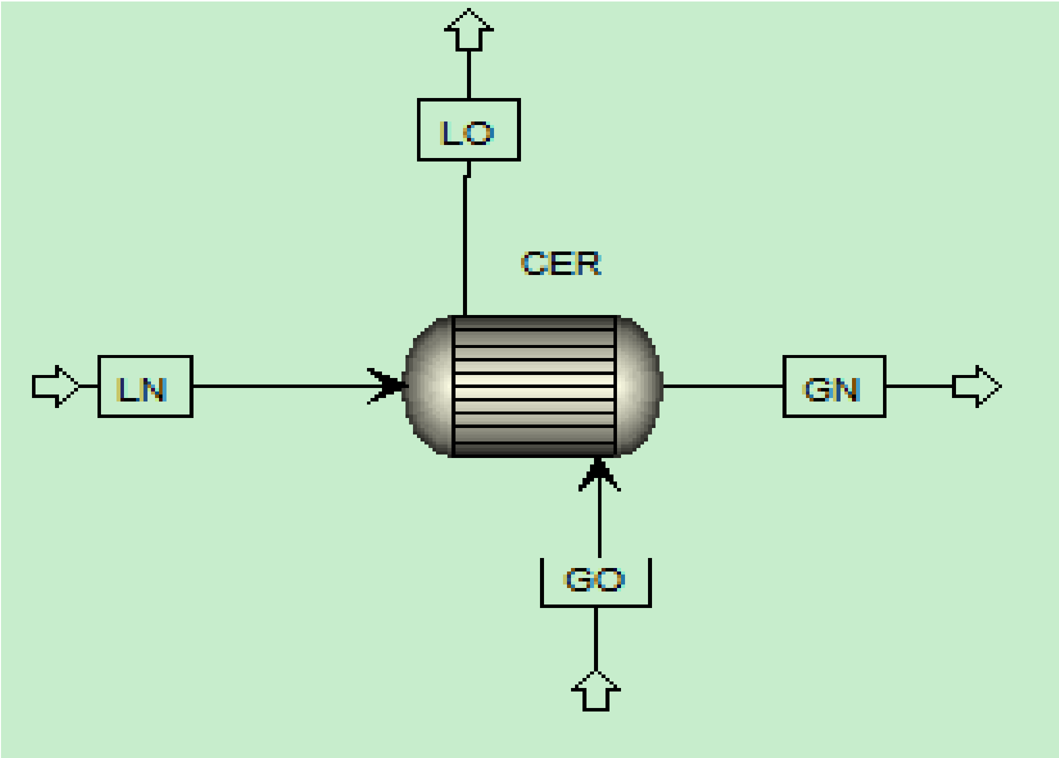

Fig. 10(a). Diagram of the cold energy recovering unit in Aspen Plus for liquid nitrogen and gaseous oxygen

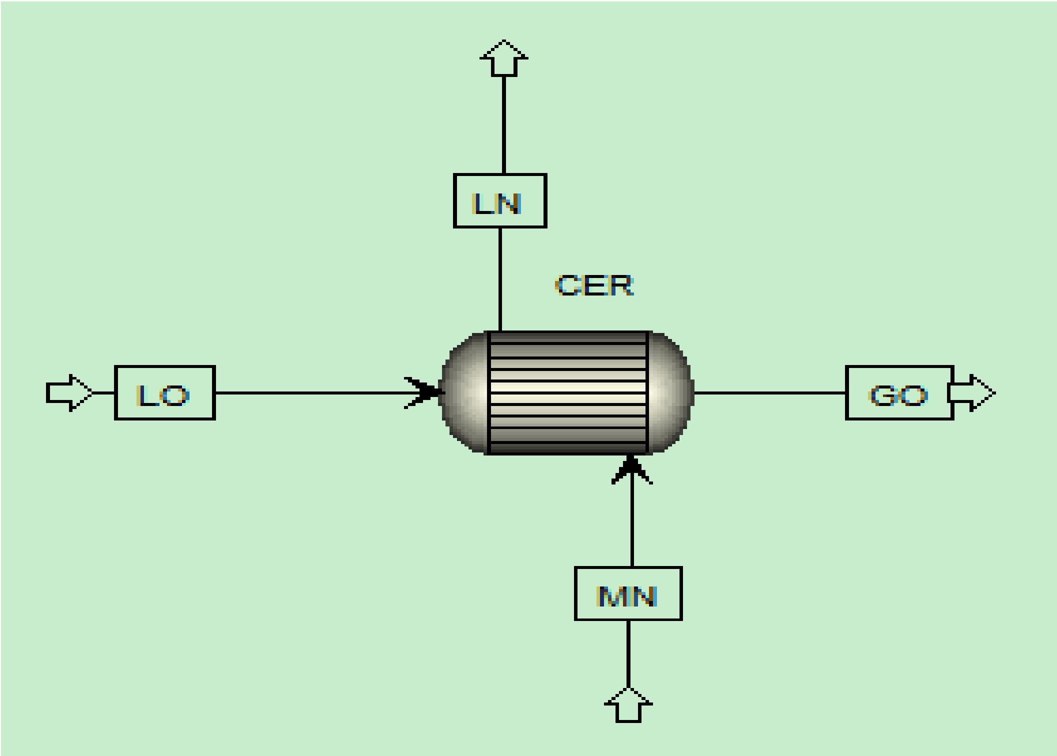

Fig. 10(b). Diagram of the cold energy recovering unit in Aspen Plus for liquid oxygen and gaseous nitrogen

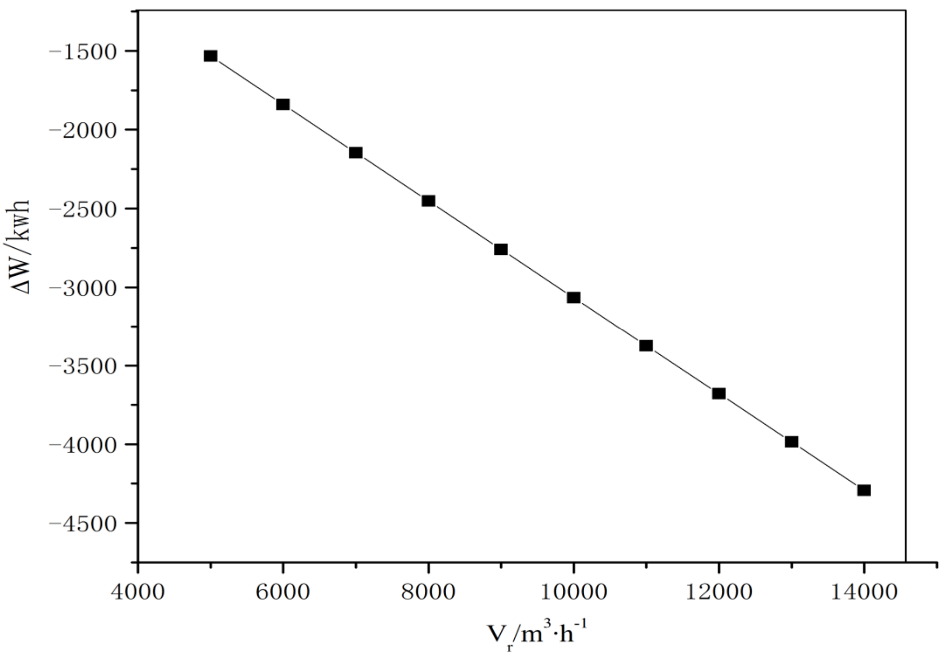

Fig. 11. The effect of V_r on the difference of energy consumption between W_r and W_e

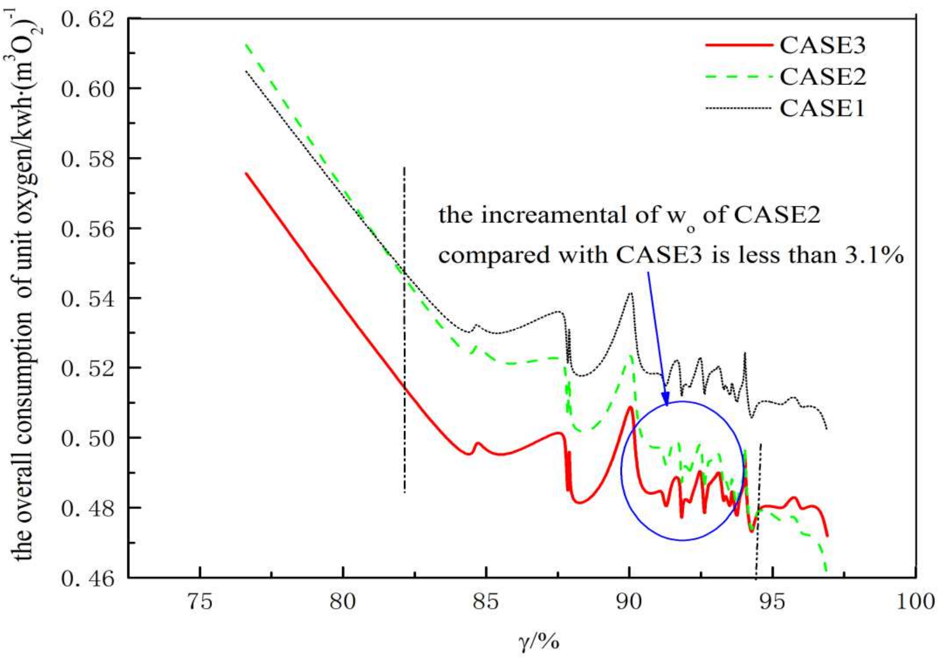

Fig. 12. The influence of the γ on the overall consumption of unit oxygen

Highlights:

- ✓ Novel regulation method of ASU to reduce the electricity consumption was proposed.
- ✓ General exergy efficiency of ASU used the new method increased by 11 %.
- ✓ Overall consumption of unit oxygen was used to evaluate energy-saving potential.
- ✓ Overall consumption of unit oxygen used CVO method reduces about 4.47 to 6.22 %.