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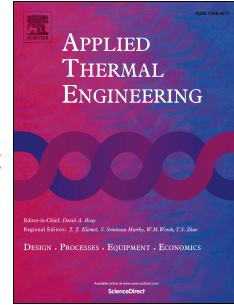
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No oxygen released of CVO

V_e
The excessive oxygen

ASU is more efficient

the consumption of unit oxygen compression
reduced more than 30 %

air

Air separtion unit

Oxygen compression and
transportationpipeline unit

Oxygen liquifaction and
vaporization unit

Gaseous oxygen to users

V_{use}

Gaseous nitrogen to users

general exergy efficiency
increases by 11% to 30%

using the cold energy recovering unit is
an energy-saving way

the overall consumption of unit oxygen/kwh·(m³O₂)⁻¹

CASE3
CASE2
CASE1

the incremental of w_o of CASE2
compared with CASE3 is less than 3.1%

γ/%

V_L

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Exergy and energy analysis of a load regulation method of CVO of air separation unit

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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

66 OCUO and the unit consumption of compression of CVO reduced more than 4.47 %

67 and 30 %, respectively. It means that CO_2 emission of every reduction 1 % of gaseous

68 oxygen release in a year in Chinese iron and steel industry will contribute

69 approximately 0.75 % to the 2020s CO_2 emission reduction target of China.

70 **Key words: air separation unit; variable load; exergy analysis; energy**

71 **consumption; CO_2 emission**

72 1 Introduction

73 Chinese iron and steel industry has become the largest crude steel producer in the

74 world since 1996[1], the iron and steel industry requires quantities of high-purity

75 industrial gas which would be 100 ~ 140 m^3 of O_2 per ton of steel, 100 ~ 140 m^3 of N_2

76 per of ton steel and 3 ~ 4 m^3 of Ar per ton of steel. For the process of direct reduction

77 iron making, the oxygen demand should be 550 to 650 m^3 per ton of steel [2].

78 According to a report by World Steel Association in 2013, 779.04 million ton of crude

79 steel in mainland China [3] accounts for 49.23 % of the total production of the whole

80 world. It means that from 7.79 to 10.91 billion m^3 of O_2 is consumed by the Chinese

81 iron and steel industries. The electricity cost of cryogenic air separation unit (ASU) is

82 more than 10 billion US dollars in 2010[4]. The electricity consumption of the iron and

83 steel industry is about 15.2 % of the total electricity consumption in China in 2007 [5],

84 in which the electricity consumption of ASU and the oxygen compression and

85 transportation pipeline (OCTP) unit is about 14 % of the total electricity consumption

86 of iron and steel industries in China[6]. The data is steady in recent years. The net

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87   demand for electricity of the industrial gases industry is 31,460 million kilowatt hours

88   (kWh) in the USA in 1998[7]. The demand increased to 39,431 million kWh in 2010,

89   which accounts for 2.8 % of the total electricity purchased by the manufacturing

90   industry and is an increase of 25.4 % compared with the amount in 1998[8]. Due to the

91   high electricity consumption of industrial gases industry, it's meaningful to reduce its

92   electricity consumption by researching new load regulation method of ASU.

93   Most of the iron and steel industries in China have their own gas production

94   plant in which multiple ASUs operate together to supply whole customers of

95   industry or other customers rather than supply product via pipeline to multiple

96   customers [9]. The gaseous production from ASU is compressed into the OCTP unit to

97   transport to the customers. With large-scale ASU as well as large-scale blast furnaces

98   and converters, the contradiction between supply and demand of gaseous oxygen (GO)

99   has become increasingly prominent because oxygen demand in fluctuation, which

100 causes the oxygen release ratio (ORR, defined as the proportion of the amount of

101 released oxygen product to the oxygen production capacity of ASU) of China to

102 increase. To decrease the ORR in China, three measures were taken. The first is

103 automatic load control (ALC) technique. The second is the variable oxygen (VAROX)

104 supply technique made by the Linde Group [10]. The third is using the liquefaction unit

105 (LU) to liquefy excessive gaseous oxygen (EGO) into a liquid product tank [11~13].

106 However, the load transition speed of ALC is slow [14, 15] and the ALC should be

107 configured for each ASU. Moreover, load regulation of ALC and VAROX would

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108   change the distillation conditions of ASU [16]. In 2010, the average ORR in Chinese

109   large-scale ASUs is more than 3.0 % [11], with an example of Hangzhou Hangyang Co.

110   Ltd which uses ALC as its ORR is 3.75 % [17]. The liquefaction capacity is also

111   limited by the capacity of the liquid product tank. The other countries' gas production

112   plant also consumed large amount of electricity purchased by the manufacturing

113   industry. Therefore, researching new operation strategies to reduce the ORR will

114   result in substantial economic benefits.

115   For variable load regulation (VLR) of ASU, the load regulation method to

116   change the distillation operation conditions such as ALC is called the internal VLR

117   method. The regulation method to change product flow and pressure in OCTP unit is

118   called the external VLR method. The variable load regulation method combining

119   ALC and LU is called Combine Variable Oxygen (CVO) supply method. This novel

120   method is as follows. Variable load operation of ASU uses ALC, combining

121   liquefaction unit in which the EGO is liquefied by LU or the cold energy recovery

122   (CER) unit using cold from liquid oxygen (LO) or liquid nitrogen (LN) from a storage

123   tank. The exergy analysis of ASU and liquefaction process of CVO is carried out. The

124   electricity consumption of ASU with CVO is compared and evaluated with the

125   electricity consumption of ASU with ALC. It provides guidance for reducing of the

126   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

148   product demand is not fixed but intermittent, especially the converter smelting process

149   where oxygen demand lasts 15 minutes while the whole cycle lasts 30 minutes.

150   Secondly, the down-regulation of the load according to the demand of one production

151   may lead to insufficient supply of another gaseous product, because the large-scale

152   ASU is a multi-product production equipment in which the production and purity of

153   one product is related to that of the other products. Moreover, the ASU would be

154   more efficient while it operates under rated load as described by Li [19].

155   Therefore, load regulation of ASU is necessary not only to take the distillation

156   operation stability of ASU and make the balance between the production and demand

157   for each product of ASU, but also to match the customer demand with the transition

158   speed of load regulation of ASU. With the development of the production technology

159   of iron and steel industry, the ASU has to run under a load condition meeting the

160   increasing demand for GN and argon (Ar). At such load condition, more GO could

161   not be consumed leading to more EGO being released. With oxygen supply system as

162   an example, the CVO is analyzed.

163   2.2 CVO regulation method

164   Fig.1 shows the principle of oxygen system of ASU with CVO, which consists of

165   ASU, OCTP unit, and oxygen liquefaction and vaporization unit. The product load

166   rate γ is defined as Eq. (1). The γ means the load rate of oxygen production in this

167   paper unless specified otherwise.

168
$$\gamma = \frac{V}{V_n} \times 100\% \qquad (1)$$

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

170   (1) The internal VLP method for ASU: the γ is increased closely to 100%

171 (described as section 4.1). Then, the ASU operates steadily at some constant γ, until a

172 substantial reduction of the gaseous oxygen demand lasts for more than 4 hours (such

173 as the annual repair of the blast furnace).

174   (2) The external VLP method for OCTP unit and oxygen liquefaction and

175 vaporization unit: The discharge pressure of valve 9 (see in Fig.1) is set as 1.5 MPa

176 and the average pressure of OCTP unit is maintained around 1.5 MPa. At trough

177 hours when the pressure of OCTP unit is greater than $(1.5+\Delta p)$ MPa, the EGO is

178 pressurized first by an oxygen compressor and then is liquefied by the LU 12 and

179 CER unit 14 to store in the liquid tank 13. At peak hours, the oxygen demand

180 increases while the production of ASU is not enough, the GO is taken from sphere

181 tank 10 or LO evaporator 14. The principle of operation of CER unit is making the

182 liquid product exchange heat with gaseous product so that the cold energy in the

183 liquid product could be recovered. The Δp is influenced by the capacity of OCTP unit.

184 The volume of the EGO to be liquefied is shown as Eq. (2).

185
$$V_l = V_e = V - V_{use} \tag{2}$$

186   In the circumstances described in (1), the down-regulation of load is carried out

187 in ASU by ALC, and the EGO is liquefied into liquid storage tank by oxygen

188 liquefaction and vaporization unit consisting of LU, CER, liquid tank and LO

189 evaporator.

190   With the increase in γ of ASU, the amount of GO product would also raise so

191   that the instantaneous larger GO demand in steelmaking process could be met.

192   Besides, the EGO could be liquefied into a liquid tank by the oxygen liquefaction and

193   vaporization unit, stopping oxygen from being released; When the GO demand

194   becomes larger, the LO could be evaporated to users. Thus, with increased production

195   and storage of GO, the contradiction between continuous production of ASU and

196   fluctuant demand of users can be solved.

197   The LU of CVO, shown as Fig.2 (a), is used to liquefy the EGO. The

198   low-pressure nitrogen from ASU, mixed with the nitrogen out of heat exchanger HE5,

199   is compressed by a nitrogen compressor. Then part of the low-pressure nitrogen goes

200   through the expander ET2 to a low pressure and produces cold energy for HE5. The

201   other part of the low-pressure nitrogen undergoes two stages of booster compressors

202   BC and then is cooled by the water coolers. The nitrogen is cooled by heat exchanger

203   HE5 and HE6. Most of the nitrogen is withdrawn to expander ET3 to a specific

204   temperature; the other part of the nitrogen is cooled by heat exchanger HE7 to be LN.

205   The feed oxygen gas undergoes the heat exchangers HE5, HE6 and HE7 to be

206   liquefied as LO.

207   The CER unit including liquid product storage tank, plate heat exchanger (HE8)

208   and several throttle valves, shown as Fig.2 (b), was similar to the device in ref. 20 and

209   ref.21. The GO from OCTP system undergoes the heat exchanger E8 and then is

210   liquefied as LO, while the LO from liquid tank is vaporized in HE8 and then is sent to

211   OCTP system.

212   Switching time from full-liquid nitrogen conditions to full-liquid oxygen

213   conditions is about 10 minutes. Under full liquid oxygen conditions, the maximum

214   oxygen production liquefied from gaseous oxygen is 8,750 $m^3 \cdot h^{-1}$. The liquefaction

215   capacity of the CER unit is 5000 $m^3 \cdot h^{-1}$ and its start-up time is 4 min. Therefore, the

216   oxygen supply can be reduced by 13,750 $m^3 \cdot h^{-1}$ within 10 minutes. For example, if

217   applying the CVO, the transition speeds of eight ASUs with product capacity of

218   102,000 $m^3 \cdot h^{-1}$ would be 1.35 % of rated load per minute and is twice the transition

219   speed of the ASU with ALC. For example, the pressure of OCTP unit at different time

220   is shown in Fig.3. Fig. 3 shows the fluctuation of the pipeline pressure, which can

221   reflect the change of gaseous oxygen demand. Therefore, the shorter the transition

222   time of load change, the quicker the users' demand is met.

223   The following summarizes three advantages of the CVO regulation: 1) The ASU

224   is running closely to rated load (detailed analysis shown in section 4.3), thus the

225   efficiency of the ASU is higher. 2) The pressure of OCTP unit runs at lower level to

226   reduce the energy consumption of compression. 3) The EGO is liquefied by the LU

227   and CER unit so that the ORR is lower and the LO production is higher. Moreover,

228   the transition speed of CVO is faster than of ALC described as in section 2.2.

229   However, the total energy consumption may increase because the LU would consume

230   a lot of electricity.

3 Exergy analysis of ASU with CVO regulation method

231

232   Based on the exergy analysis, a 40,000 $m^3 \cdot h^{-1}$ of external ASU with CVO

233   regulation method and the liquefaction system have been evaluated and the exergy

234   efficiency of single ASU is compared with the ASU combing LU .

235   3.1 A TYPICAL EXTERNAL COMPRESSED CRYOGENIC AIR SEPARATION PROCESS

236   The external ASU studied in this paper uses the principle of two-column

237   separation based on a low- and high-pressure distillation column, shown as Fig. 4[22].

238   Air is firstly compressed in the main air compressor (AC), and then purified to

239   remove the primary impurities such as H_2O, CO_2, and C_2H_2 via molecular sieves

240   absorbers (MS). Part of the pure air is cooled in the main heat exchanger (MHE1) to

241   saturation temperature and enters the lower column (C1). The others enter a

242   turbocharger; then the air is cooled in HE1 to 164 K and is expanded in an expansion

243   turbine (ET); subsequently, the air enters the upper column (C2). The crude argon

244   column (C701, C702 and C703) is configured in the cold box. The product index is

245   shown in Table 1.

246   3.2 The exergy efficiency

247   According to Chinese GB/T 14909-2005, named the technical guides for exergy

248   analysis in energy system, the exergy and the general exergy efficiency [23] is

249   calculated by Eq. (3) and Eq. (4), respectively.

250
$$E_m(T,p) = \sum x_i E_{m,i}(T,p) + RT_0 \sum x_i \ln \frac{f_i}{f_{i0}} + (1 - \frac{T_0}{T})\Delta_{mix} H_m \qquad (3)$$

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251
$$\eta_{\text{gen}} = \frac{E_{out}}{E_{in}} = 1 - \frac{I_{\text{int}}}{E_{in}} \qquad (4)$$

252   The exergy balance of ASU is shown as Fig.5 (a). The LU can be under three

253   conditions these are full-LO condition without LN production, full-LN condition

254   without LO production and liquid oxygen-nitrogen condition. The exergy balance of

255   LU under full-LO condition is shown as Fig.5 (b), whose total exergy inputs consist

256   of the exergy in the feed and the electricity consumption while the total exergy

257   outputs consist of the exergy of LO and cold water. Similarly, the exergy balance of

258   LU under full-LN condition is shown as Fig. 5(c), whose total exergy inputs consist of

259   the exergy in the feed and the electricity consumption while the total exergy outputs

260   consist of the exergy of LN and cold water.

261   The exergy calculation software for oxygen-nitrogen-argon mixed working fluid

262   based on Peng–Robinson equation of state was developed by VC ++ 6.0 [24].

263   The general exergy efficiency (GEE) of ASU and LU is shown in Table 2 and

264   Table 3. The GEE of ASU combined with LU under full-LO condition and full-LN

265   condition is 26.33 % and 31.23 % respectively, which is 1.11 times and 1.31 times of

266   than that of single ASU respectively. It indicates that the process of ASU with LU

267   would be more efficient.

268   4 Energy analysis of the CVO regulation method

269   Exergy is the useful analysis method of an amount of energy that can be equally

270   converted into work. Exergy analysis can be used to indicate thermodynamic

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271   efficiency of a process, including all quality losses of materials and energies. While

272   an energy analysis of a system is able to evaluate the energy consumption of the

273   proposed strategy. The energy analysis for air separation unit, OCTP unit and oxygen

274   liquefaction and vaporization unit is carried out in this section.

275   4.1 the energy analysis of the air separation unit

276   The electricity consumption of ASU varies with γ. Based on JBT 8693-1998,

277   named standard for large and medium scale air separation unit; the consumption of

278   unit oxygen (CUO) is calculated by Eq. (5). The CUO represents the electricity

279   consumption of one m^3 of GO.

280
$$w_{O_2} = \frac{W_{ASU}}{V_1 + 3\sum V_{lj}} \tag{5}$$

281   where W_{ASU} is the total electricity consumption for ASU production, including the

282   electricity of the main air compressor, auxiliary device and workshop.

283   To find effects of various γ on the electricity consumption of ASU, the CUO is

284   calculated. Based on the actual operation data of the 40,000 $m^3 \cdot h^{-1}$ ASU, the result is

285   shown in Fig. 6. The principle of selecting such data is as follows:

286   1) Ignoring the energy consumption of air pre-purification system; 2) Ignoring the

287   effect of liquid product; 3) Based on the data including inlet airflow, gaseous oxygen

288   flow and gaseous oxygen flow at rated load, both the inlet air flow and gaseous

289   product flow changes in the same proportion, according to ref. [25].

290   The CUO has dramatic changes with various γ. With increasing the γ, the CUO

291   reduces gradually until γ is equal to 100 %. Then the unit consumption of ASU begins

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292 to increase if the γ continues to increase. The ranges of the unit consumption of ASU

293 with different γ is from 0.459 to 0.425 kW·h ·$(m^3O_2)^{-1}$. The CUO with γ of 80 %

294 increases by 5.99 % compared to the one with γ under rated load condition. The effect

295 of the load regulation process on the CUO is significant. It means that the appropriate

296 load regulation method can save energy.

297 4.2 The electricity analysis of the oxygen compression and transportation

298 pipeline unit

299   Thus the electricity consumption of OCTP unit would induce further if the

300 pressure of it decreases to 1.5 MPa as described in section 2.1. The electricity

301 consumption of OC in OCTP unit is calculated by Eq. (6) [26]. Part of the

302 compressibility factor A calculated by the program developed in section 3.2 is listed in

303 Table 4.

304
$$w_{com} = \frac{1}{\mu}\frac{k}{k-1}AR_m T\left[\left(\frac{p_{out}}{p_{in}}\right)^{\frac{k-1}{k}}-1\right]$$
(6)

305   Ignoring the exergy of cold water and the exergy loss of the compressed oxygen

306 into the OCTP unit, the exergy analysis of the OC in OCTP unit is carried out. Its

307 exergy inputs include the exergy of inlet oxygen and electricity consumption feeding

308 to the OC and its exergy outputs include the exergy of outlet oxygen.

309   Fig. 7 shows the effect of different discharge pressures of oxygen/nitrogen

310 compressors on the electricity consumption, general exergy efficiency and exergy loss

311 of that. In Fig. 7 (a), with the discharge pressure of the OC decreasing from 3.04MPa

312 to 1.5MPa, the electricity consumption and exergy loss of the OC reduces 30.22% and

313 38.38% respectively, while its general exergy efficiency increases from 59.67% to

314 67.33%. Thus in order to save electricity, it is very necessary to decrease the pressure

315 of OCTP unit. Similarly, the electricity consumption, general exergy efficiency and

316 exergy loss of the nitrogen compressor at different discharge pressure are shown in

317 Fig. 7 (b).

318 4.3 Comparison of three evaluation methods at different load regulation methods

319 The total electricity consumption includes that of ASU, the OCTP unit and

320 oxygen liquefaction and vaporization unit. The total electricity consumption on three

321 cases is compared. For CASE 1, the ALC is used on ASU as described section 2.1.

322 For CASE 2 and CASE 3, the CVO is applied on ASU. The γ in CASE 2 raised only

323 5 % than before while the γ in CASE 3 increases to 100 %. The γ is made equal to

324 100 % in the above comparison process especially when the (γ +5 %) is larger than

325 100 %. Moreover, it is assumed that there is enough space for liquid storage tanks.

326 The total electricity on CASE 1, CASE2 and CASE3 is calculated by Eq. (7), Eq.

327 (8) and Eq. (9) respectively. Where V_{CASE1} is the production of ASU in CASE 1; V_{use}

328 is the user's demand; V_l is the EGO to be liquefied; w, w_{com} and w_l is the consumption

329 of unit oxygen, the consumption of unit oxygen compression and the consumption of

330 unit oxygen liquefaction respectively. The $V_{CASE1} \cdot w$, $V_{use} \cdot w_{com}$ and $V_l \cdot w_l$ in Eq. (7)

331 represent the CUO, the electricity of OCTP unit and the electricity of oxygen

332 liquefaction and vaporization unit.

333
$$W_{CASE1} = V_{CASE1} \cdot w + V_{use} \cdot w_{com} + V_l \cdot w_l \tag{7}$$

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334 $$W_{CASE2} = V_{CASE2} \cdot w + V_{use\ CASE2} \cdot w_{com} + (V_{CASE2} - V_{use\ CASE2}) \cdot w_L \qquad (8)$$

335 $$W_{CASE3} = V_{CASE3} \cdot w + V_{use\ CASE3} \cdot w_{com} + (V_{CASE3} - V_{use\ CASE3}) \cdot w_L \qquad (9)$$

336   The consumption of unit oxygen, calculated by Eq. (10), is fitted by the data

337 derived from Fig.6. The consumption of unit oxygen compression is obtained by

338 Eq.(6) . The consumption of unit oxygen liquefaction is achieved from the actual data.

339 When 8,750 $m^3 \cdot h^{-1}$ of oxygen is liquefied, the electricity consumption of LU is 4,

340 956.52 $kW \cdot h \cdot h^{-1}$, thus the consumption of unit oxygen liquefaction is 0.57

341 $kW \cdot h \cdot m^{-3} O_2$.

342 $$w = 0.44277 + \frac{-0.8353}{(18.83801 \times \sqrt{\pi/2})} \times e^{(-2 \times ((v - 98.99815)/18.83801)^2)} \qquad (10)$$

343   The daily data of supply and demand as well as liquefaction and release of

344 oxygen during 59 days in 2009 is shown in Fig.8. The V is always beyond V_{use}. As

345 the data in Fig.8 is randomly selected, the results could be used to analyze other days

346 of the year 2009.

347   The effect of γ on the total electricity consumption on the three cases (CASE 1,

348 CASE 2 and CASE 3) is shown in Fig. 9. The increase of γ suggests an increase of the

349 total energy consumption of CASE 1 and CASE 3 as well as the gradual reduction of

350 the total energy consumption of CASE 2. When γ varies from 84 % to 95 %, The

351 descending order of the electricity consumption on the three cases is CASE 2, CASE

352 3 and CASE 1, but the electricity consumption on CASE3 is closer to that on CASE 1.

353 While γ is greater than 95 %, the electricity consumption of CASE 2 is the lowest

354 among the three cases. It means that the total electricity consumption is influenced by

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355 the γ. For several points in Fig.9, for example γ is equal to 76 %, 87 % and 90 %; the

356 value of V_0/V_{use} is greater 1.04. Thus, it can be referred that the EGO should be

357 released rather than be liquefied if the value of V_0/V_{use} is greater than 1.04.

358 The electricity consumption of CASE 2 is the lowest among the three cases

359 while γ is greater than 95 %, hence the CASE 2 should be studied further by applying

360 CER. The amount of EGO liquefied by CER is V_r. The medium pressure nitrogen

361 (MN) is liquefied by LO to be LN which is used to liquefy the EGO.

362 Fig.10 shows a flow diagram of the cold energy recovering unit in Aspen Plus.

363 Where, (a) represents that 1 $kmol·h^{-1}$ EGO is liquefied by LN and (b) represents that 1

364 $kmol·h^{-1}$ MN is liquefied by LO. Table 5 shows the simulation conditions of CER

365 process.

366 The simulation results show that liquefying 1 $kmol·h^{-1}$ EGO need about 0.89

367 $kmol·h^{-1}$LN, which means that the ratio of EGO and LN is 1:0.89; Liquefying 1

368 $kmol·h^{-1}$ MN need about 1.6 $kmol·h^{-1}$LO, which means that the ratio of LO and MN is

369 1.6:1. Such ratio would not change until the temperature and pressure of product in

370 table 5 changed.

371 The energy consumption of CER unit consists of the electricity consumption of

372 MN compression and the cold loss of liquid product exchanging heat with gaseous

373 product.

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

375 $$W_N = V_r \cdot 0.896 \cdot w_N \tag{11}$$

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376 where W_N is the electricity consumption of MN compression; the w_N is the unit

377 consumption of nitrogen compression, shown as Fig.7 (b).

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

379 $$Q = V \cdot c_p \cdot \Delta t \tag{12}$$

380 where Q is cold loss; c_p is heat capacity at constant pressure; Δt is the temperature

381 difference at warm end of CER unit.

382   Based on the conditions in table 5, the total energy consumption can be

383 calculated by Eq. (13).

384 $$W_r = V_r \cdot 0.896 \cdot w_N + \frac{V_r \cdot 0.94239 \cdot \Delta t_O}{3600} + \frac{V_r \cdot 1.0482 \cdot \Delta t_N}{1.6 \times 3600} \tag{13}$$

385   If the CER is not applied, the EGO would be released. The electricity due to the

386 EGO released is calculated by Eq. (14).

387 $$W_e = V_r \cdot w \tag{14}$$

388 where W_e is the electricity of EGO released; w is the unit consumption of oxygen,

389 shown as Fig. 6.

390   The difference of energy consumption between CER unit and EGO released is

391 set as ΔW. Fig. 11 shows the effect of V_r on such difference of energy consumption. It

392 indicates that if the ASU operates stable, W_r is always smaller than W_e, which means

393 that the total energy consumption of CER unit would decrease with increasing V_r.

394 Thus, applying the CER unit is an energy-saving measure.

395   The CUO is selected to evaluate the electricity consumption of various methods.

396 Table 6 lists the average of the CUO of the above three cases during 59 days in Fig. 8.

397 Regardless of electricity consumption of liquefaction, the CUO of CASE 2 and CASE

398 3 compared to CASE 1 reduce by 2.73 % and 1.82 % respectively, and the unit

399 consumption of oxygen compression decreases by 30 %.

400 Table 6 also reveals that the unit consumption of oxygen liquefaction is greater

401 than of ASU and compression, which means that the electricity consumption of OCTP

402 unit would increase because of using LU.

403 To evaluate the actual energy-saving potential of CVO method further, the

404 overall consumption of unit oxygen (OCUO) is selected. The OCUO is defined as the

405 ratio of the total electricity consumption and the actual amount of gaseous product V_i

406 including the gaseous product consumed and stored but not including the released

407 gases. The OCUO is calculated as Eq. (15) [27]. The other product capacities of a

408 multi-product production ASU should be converted into oxygen product capacity, the

409 converted factor can be obtained by the minimum separation work of each component

410 calculated by Eq. (16)[27].

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

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

$$N = nRT \sum y_i \ln \frac{1}{y_i} \tag{16}$$

414 It is assumed that air consists of O, N and Ar where the mole fraction of them is

415 20.95%, 78.12% and 0.93% respectively. The minimum separation work of one mole

416 of air to be separated is 62.4 kJ $\cdot(m^3 air)^{-1}$.

417   Thus the minimum separation work of oxygen is:

418    $N_1 = N/y_1 = 297.80 \ kJ \cdot (m^3O_2)^{-1}$

419   And the minimum separation work of argon is:

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

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

422   Fig. 12 shows the influence of γ on the w_O on the three cases. An increase of γ

423   shows a reduction of the w_O. The w_O under CASE 3 and CASE 2 reduces 6.22% and

424   4.48% compared to CASE 1 respectively. When the γ is bigger than 95 %, the w_O

425   under CASE 3 is greater than under CASE 2, consistent with the releations of total

426   energy shown in Fig.9. When the γ varies between 90 % and 95 %, the w_O under

427   CASE 3 gets the minimum, and the incremental of w_o under CASE 2 compared with

428   CASE 3 is less than 3.1%. The reason for decreasing the w_O is that the V_i increases,

429   which is achieved by liquefying the EGO without oxygen released. However, the total

430   electricity consumption increases due to the liquefying process. When the γ is more

431   than 95%, the w_O under CASE 2 is minimal within the lowest total elecrictiy

432   consumption, because the whole EGO is liquefied rather than released.

433   To sum up, the CVO regulation method is influenced by γ. The CVO regulation

434   method is modified based on the actual conditions as follow. When the ratio of V_0 to

435   V_{use} is less than 1.04 and the product rate is greater than 95 %, the ASU system should

436   operate under rated load condition. While the γ varies from 85 % to 95 %, the γ should

437   be increased by 5 %. If γ is less than 85 %, the ALC should be applied to ASU system.

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438   While the ratio of V_0 to V_{use} is more than 1.04, keeping V_0 constant, the EGO should

439   be released. For example, after applying the CVO regulation method, an ASU system

440   whose production is 82,000 m^3/h and its OCTP unit in particular, achieves 1.25

441   million kWh electricity-saving due to the EGO being liquefied rather than be released.

442   In China, the total oxygen consumption is about 10.91 billion m^3 of O_2 while the

443   unit consumption of oxygen is assumed to be 0.42 kWh $\cdot(m^3 \cdot O_2)^{-1}$ in 2013. If the

444   oxygen release ratio decreases by every 1 % of the above oxygen consumption, the

445   electricity-saving would be 4.58×10^{10} kWh for ASU system. As the CO_2 emission of

446   unit electricity generated by coal-fired power generation system is 1.03 kg/kWh [28],

447   the CO_2 emissions could reduce 5.28×10^7 tons at least annually with the above

448   energy-saving. China promised to reduce the CO_2 intensity by 40-45 % by 2020 from

449   2005 levels, and China's CO_2 emission reduction must exceed 6994.9 [29] million tons

450   to fulfill the promised CO_2 emission reduction target of China in 2020. It can be

451   inferred that the CO_2 emission reduction of iron and steel industry contributes 0.67 %

452   to China's CO_2 emission reduction in 2020 if the oxygen releasing rate decreases by

453   every 1 % of gaseous oxygen consumption in 2013.

454 **5 Conclusion**

455   Aiming at achieving energy savings and reducing oxygen release ratio, the

456   exergy calculation program was devoloped. Besides, the unit consumption of oxygen,

457   the total energy consumption and the overall unit consumption of oxygen were

458   selected to determine energy-saving of different load regulation method. After that,

459   the CVO regulation method is proposed for ASU

460   Compared with the current regulation method, the CVO regulation strategy

461   presented in the paper has following features.

462   (1) The contradiction between continuous production of ASU and fluctuant

463   demand of users can be solved, because of increase of production and storage of

464   gaseous oxygen.

465   (2) The transition speed of CVO regulation method is about 3.125 %/min twice

466   as the transition speed of current regulation method.

467   (3) The general exergy efficiency of ASU combining with liquefaction unit is

468   increased by 11 % to 31 %. The OCUO is suitable method to evaluate the

469   energy-saving potential of CVO. The OCUO and the unit consumption of

470   compression of CVO reduced more than 4.47 % and 30 %, respectively. Besides,

471   using the cold energy recovering unit is an energy-saving way.

472   (4) The proposed regulation method is related to product load rate. While the

473   product load rate is more than 95 %, the ASU operates under rated load and the CVO

474   regulation method is energy-saving.

475   **Acknowledgements**

479

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

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550

551   Tables

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

Table 1. The product index of 40, 000 m³/h of ASU

Product	Production /m³·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})		$E_{out}/E_{in} \times 100\% = 23.84\%$		

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·$(m^3O_2)^{-1}$	w_{com} /kW·h·$(m^3O_2)^{-1}$	w_l /kW·h·$(m^3O_2)^{-1}$
	CASE1	0.439	0.200	0.566
CVO	CASE2	0.427	0.140	0.566
	CASE3	0.431	0.140	0.566
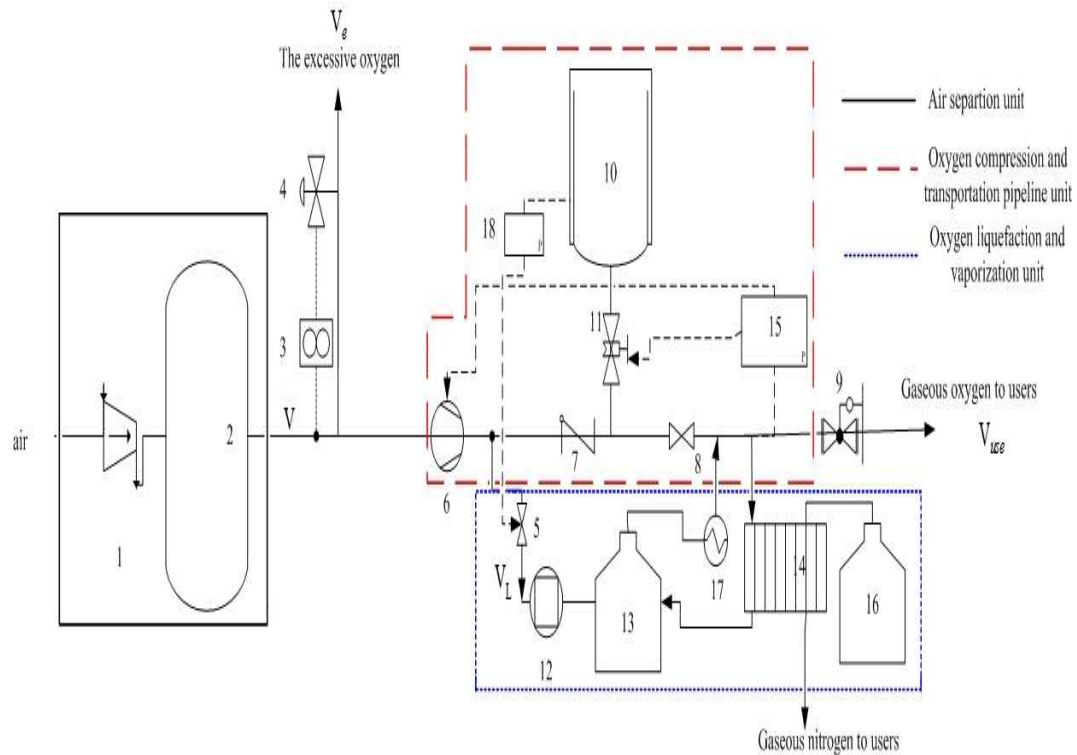
Fig. 1. Principle of oxygen system of ASU with CVO

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;

Cold water in Cold water out

Medium pressure nitrogen

NTC

Nitrogen to compresor

The excessive oxygen

HE5

ET2

BC1

Cold water in

Cold water out

HE6

ET3

BC2

Cold water in

Cold water out

HE7

Liquid oxygen

Liquid nitrogen

Nitrogen to user

heating

High pressure oxygen

heating

HE8

Blowing

blowing

Liquid storage tank

Liquid oxygen storage tank

(a)

(b)

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
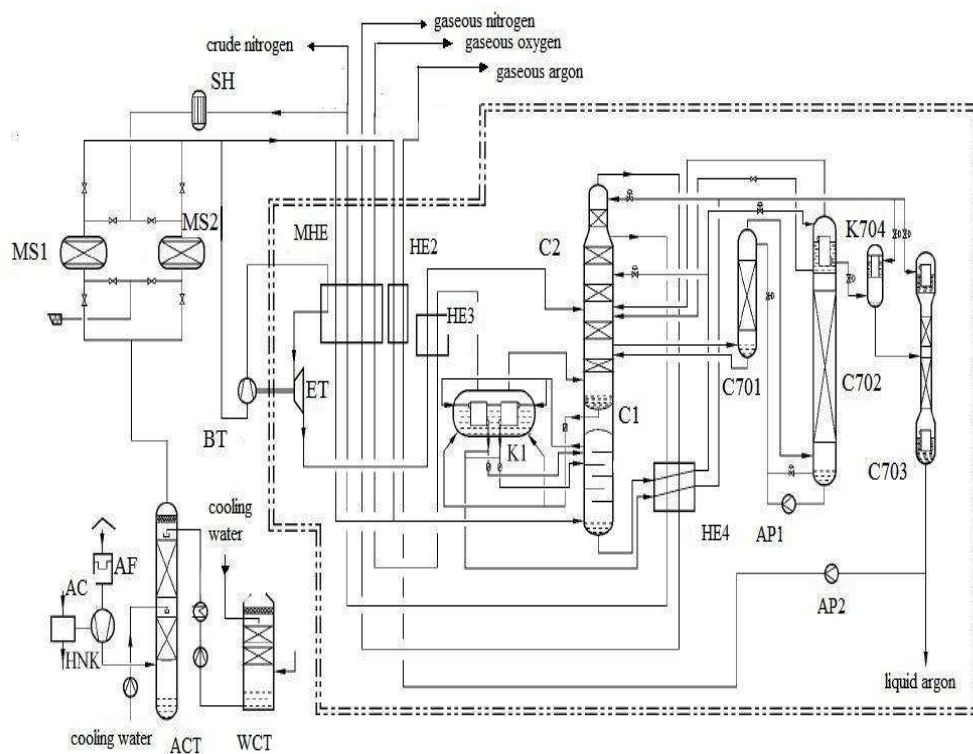
Fig. 4. Diagram of the typical externally compressed cryogenic air separation process
**AF—air filter; AC—air compressor; ACT—air cooling tower; WCT—water cooling tower;
MS—molecular sieve purifier; SH—steam heater; BT—booster turbine; ET—expand
turbine; MHE—main heat exchanger; HE2—heat exchanger of 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**
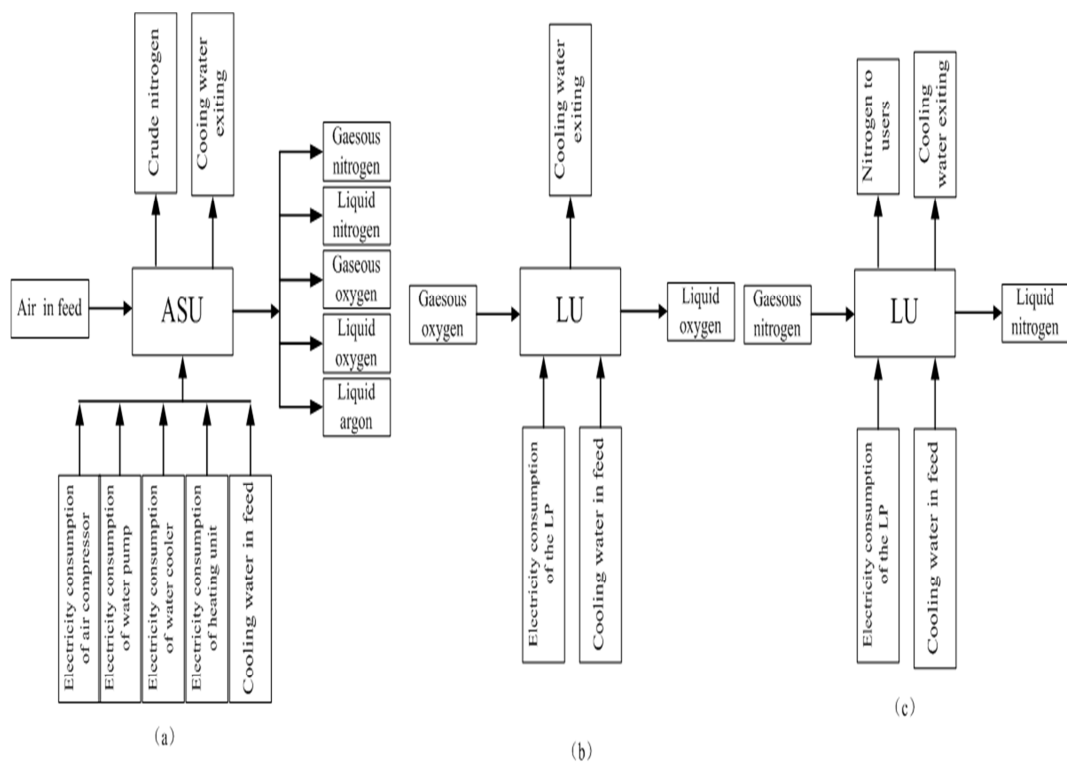
Fig. 5. The exergy balance of ASU and LU
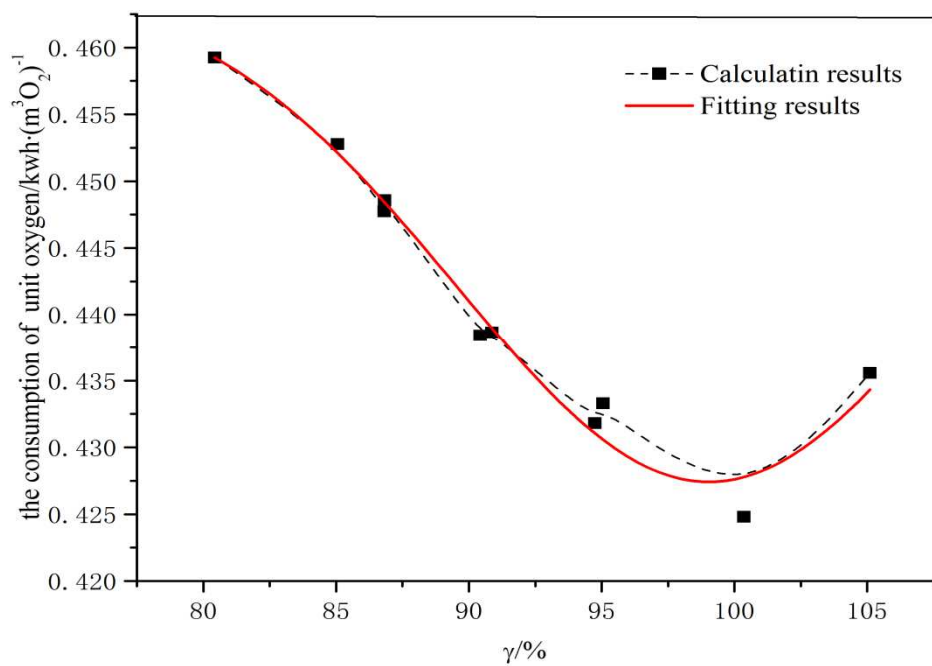
Fig. 6. The effect of γ on the consumption of unit oxygen
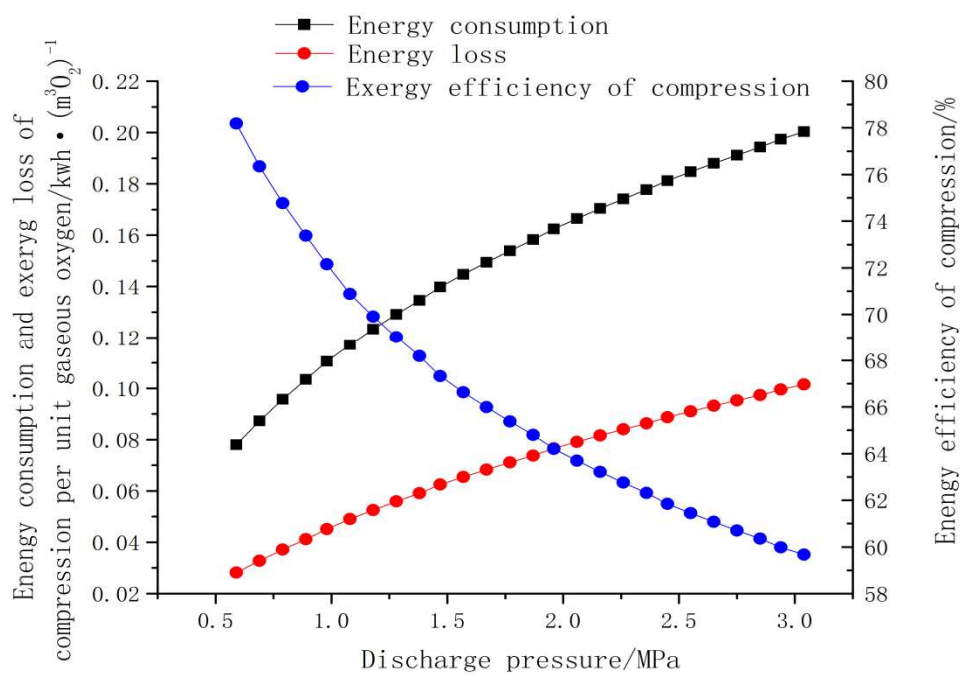
Fig. 7(a). The effect of different discharge pressure of oxygen compressor on the energy consumption, exergy efficient and exergy loss of it
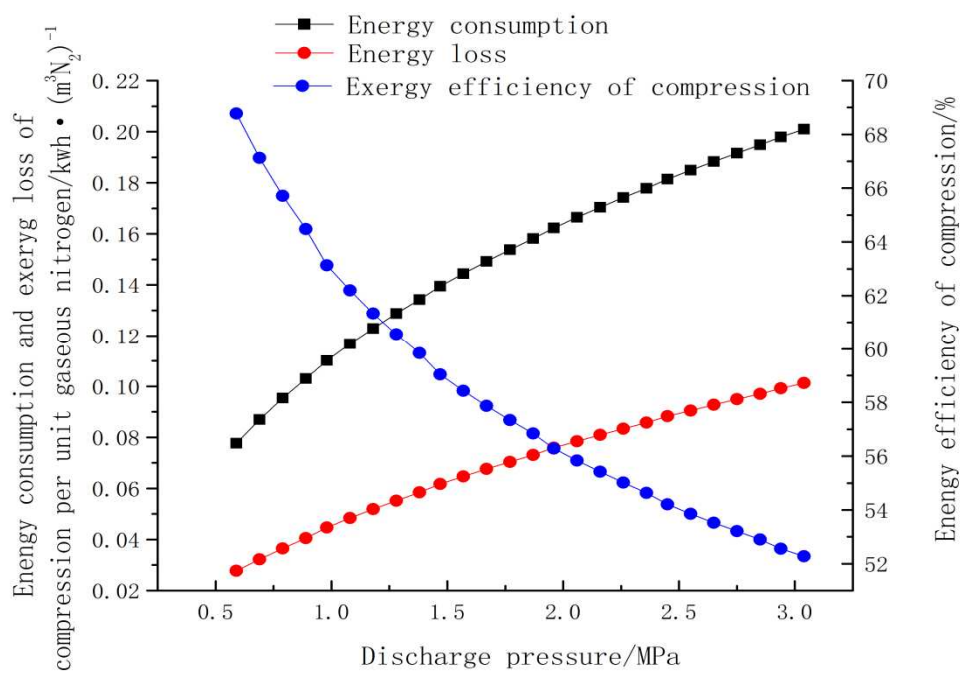
Fig. 7(b). The effect of different discharge pressure of nitrogen compressor on the energy consumption, exergy efficient and exergy loss of it
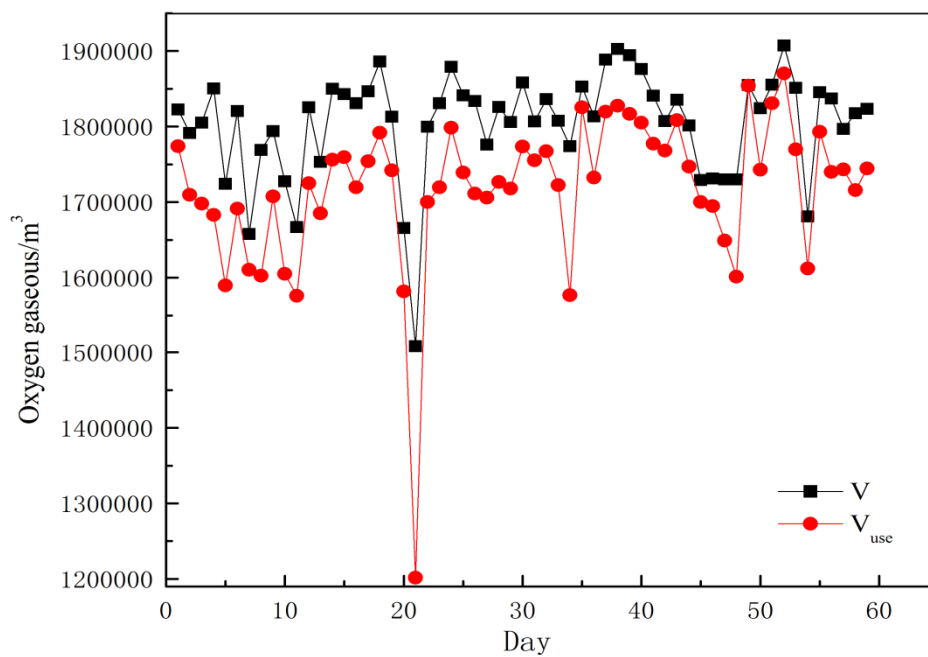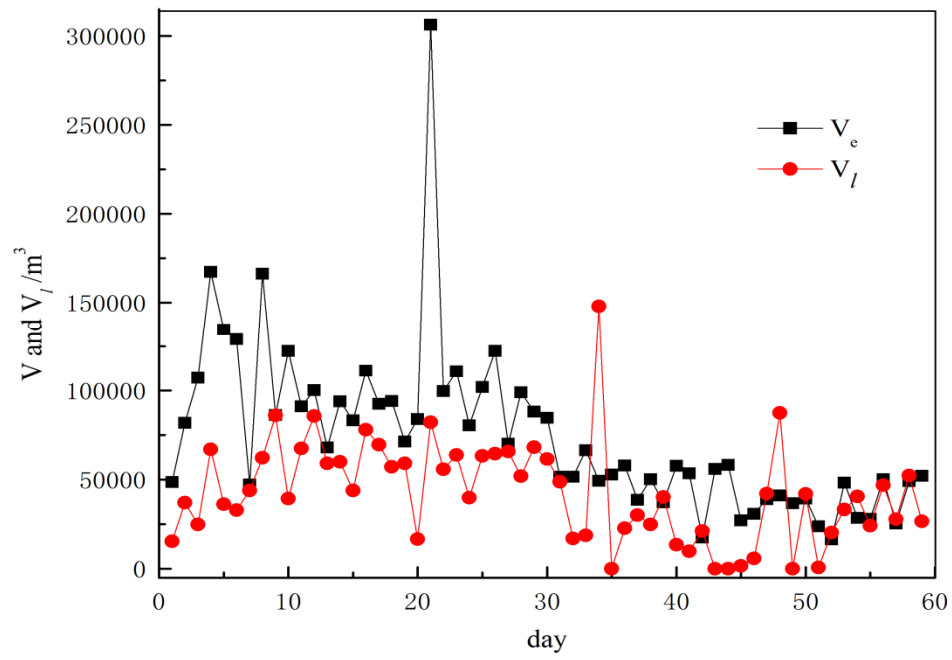
Fig. 8(a). Daily data of supply and demand of oxygen during 59 days in 2009

Fig. 8(b). Daily data of liquefaction and release of oxygen during 59 days in 2009
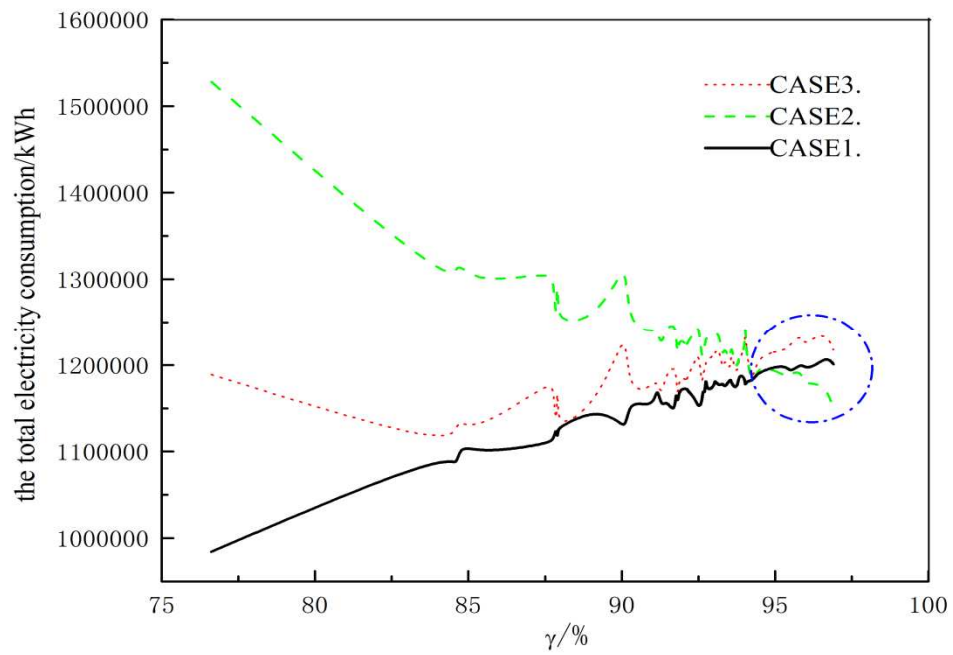
Fig. 9. The effect of γ on the total energy consumption of the three cases
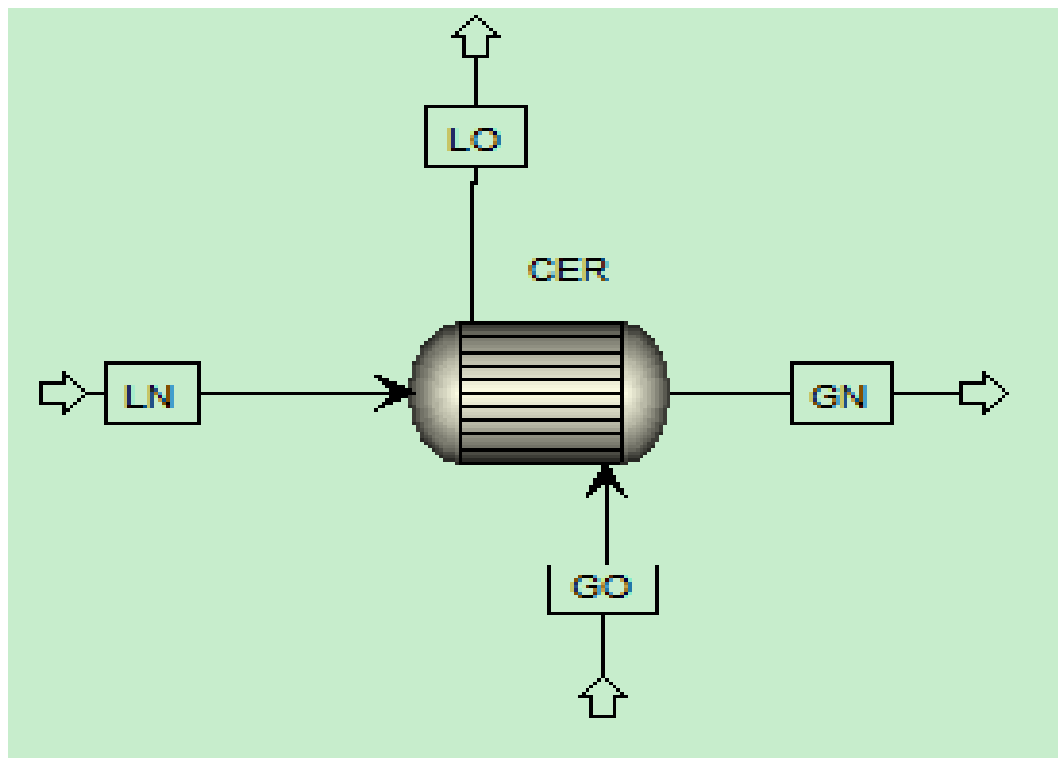
Fig. 10(a). Diagram of the cold energy recovering unit in Aspen Plus for liquid nitrogen and gaseous oxygen
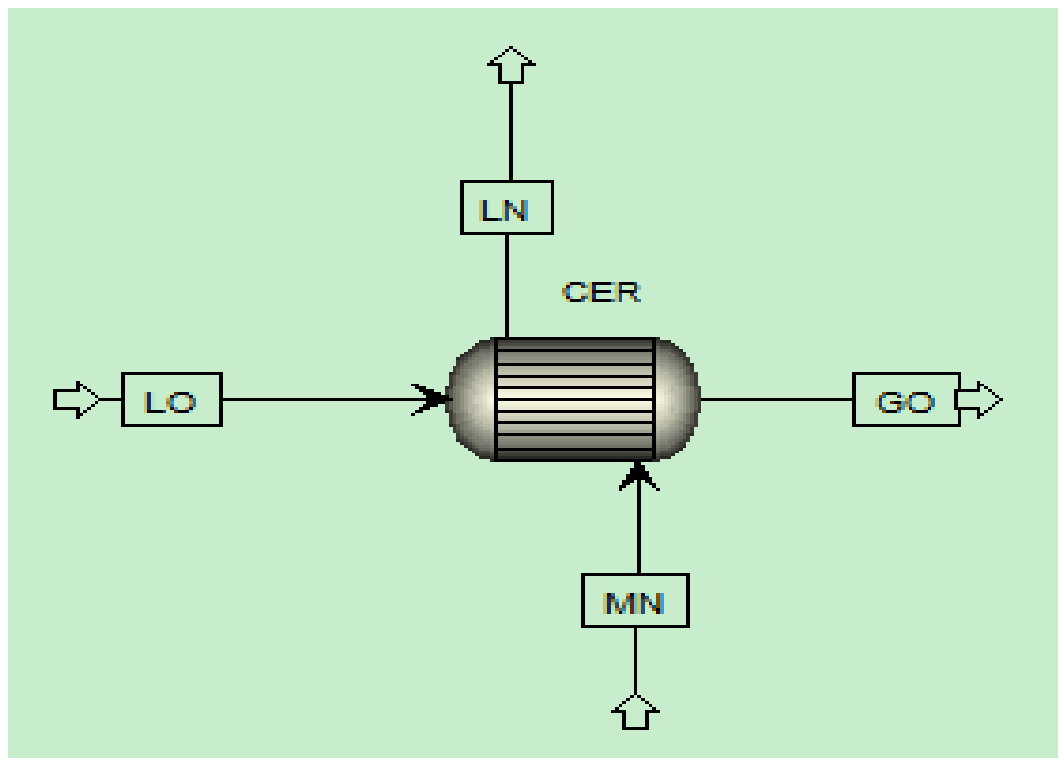
Fig. 10(b). Diagram of the cold energy recovering unit in Aspen Plus for liquid oxygen and gaseous nitrogen
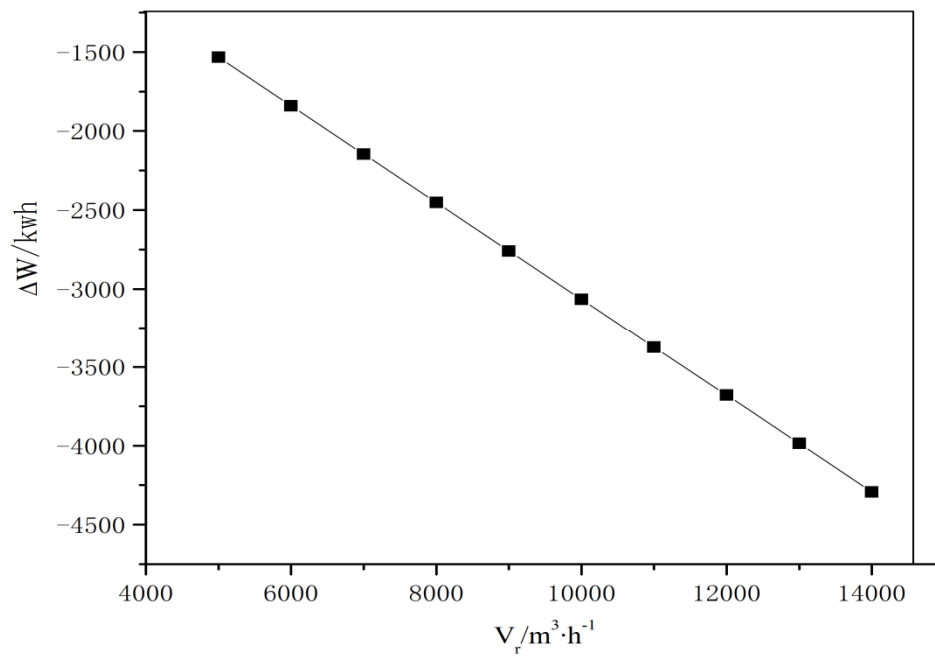
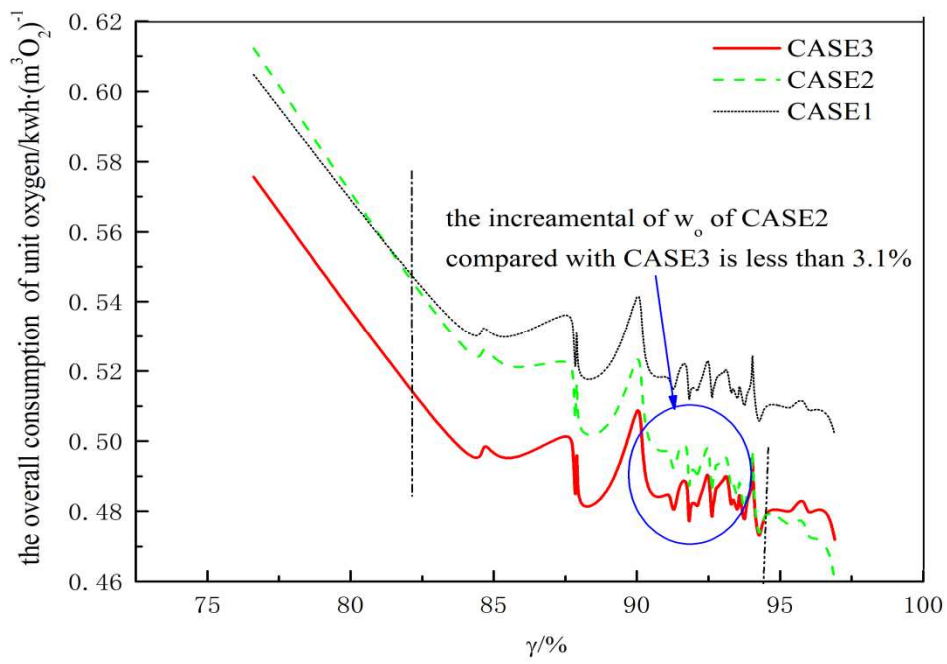**Fig. 11.** The effect of V_r on the difference of energy consumption between W_r and W_e

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 %.