Exergy analysis of an industrial air separation unit for liquefied natural gas production

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Abstract: The idea of adding compressed natural gas to the main heat exchanger of an industrial air separation unit to produce liquefied natural gas in small scale is studied. The unit effectiveness is selected as the objective function to compare air separation unit and combined LNG and air separation unit. The results indicate that 1 kg/h dry air can also produce 0.013–0.027 kg/h liquid natural gas for different operating conditions of the air separation unit. Comparing with the base air separation unit, the cold box irreversibility of the combined unit reduces approximately 5–11%, while the process effectiveness increases about 35–60% for different operating conditions.

Keywords: air separation unit; ASU; liquid oxygen; compressed natural gas; CNG; liquefied natural gas; LNG; exergy analysis; effectiveness; irreversibility; combined unit.

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1 Introduction

Among fossil fuels, natural gas is the cleanest, economical and energy efficient one (Lin et al., 2018). There are two main methods to transport natural gas; gas pipelines and liquefied natural gas (LNG) (Xu et al., 2013). When methane is the only component of natural gas, LNG is produced at –162°C, at atmospheric pressure and its volume is reduced about 1/600 of natural gas at standard state (Farhad et al., 2008). Natural gas liquefaction processes consume great amounts of electrical energy (1,000–5,000 kJ/kg for producing one kg of LNG) (Nguyen et al., 2018).

There are generally three types of refrigeration cycles for natural gas liquefaction: cascade refrigeration cycle, mixed refrigerant cycle and expander cycle (Fahmy et al., 2016), small scale liquefying natural gas (SSLNG) are plants with a capacity of less than 1 million tons per annum. Exergy analysis is employed to analyse liquefaction processes and it is mainly important from the viewpoint of energy controlling (Esfahani et al., 2017). Determining energy losses according to exergy analysis has various applications (Zeeshan et al., 2019). The convection heat transfer and the heat exchanger effectiveness in a double pipe heat exchanger are investigated numerically (Milani Shirvan et al., 2017). Exergy efficiency is a perfect inspector of design quality since it is based on thermodynamics, the use of exergy in refrigeration systems is more important due to the large power consumptions (Marmolejo-Correa and Gundersen, 2015). He and Ju (2014) developed a novel process for small scale natural gas liquefaction which used the exergy of high-pressure gas in the pipe to liquefy a portion of natural gas. The results revealed that the maximum liquefaction rate and the maximum exergy utilisation rate are 12.61% and 0.1961, respectively.

There are basically two kinds of integration of LNG and air separation units (ASUs); the application of LNG cold energy for ASU and liquefying compressed natural gas (CNG) while producing air products in ASU. In the LNG terminals, LNG is vapourised to a required temperature and pressure before entering the pipeline network, the amount of cold exergy released is about 370 kJ per kg/s (Gomez et al., 2014). Heating of LNG for regasification is a net loss of accessible energy, which decreases the energy efficiency (Kim et al., 2015), therefore, it is necessary to reserve it and increase energy and exergy efficiency of the total process. Ebrahimi and Ziabasharhagh (2017) used LNG cold energy to improve the performance of a cryogenic ASU. The results indicated 8.04% and 17.05% reduction in the power consumption and initial capital cost of ASU plant, respectively. Mehrpooya et al. (2015) designed a novel cryogenic air separation process with LNG cold energy utilisation and showed that the energy consumption was about 38.5% lower than a conventional air separation process. The energy and exergy efficiencies where also 59.4% and 67.1% greater, respectively.

In combined LNG plants and ASUs (combined units), while gaseous or liquid nitrogen (LN) and oxygen are produced, natural gas is also liquefied. Tuo and Li (2011) developed a novel combined cycle to liquefy natural gas and investigated the effect of flow rate through two stages of expanders on system performance. The results indicated that by increasing β (the flow rate ratio of two stages of expanders, β = Ve1/Ve2) from 0.5 to 2, exergy loss in heat exchange process decreased from 9.87 kW to 2.17 kW and exergy efficiency increased from 68.2% to 88.1%. Tesch et al. (2016) introduced a novel model for the integration of the LNG into an air separation process. Comparing the different cases, the exergetic efficiency of a conventional ASU increased from 38% to 49% in the combined unit.

Although many studies have been conducted in LNG refrigeration cycles, analysis performed in LNG production through ASUs are rare. Therefore, the purpose of the present paper is to study integration of the production of LNG into an ASU. Experimental analysis is performed on an industrial ASU under different operating conditions. CNG is added to the main heat exchanger (MHE) of the ASU for LNG production. Taking unit effectiveness as the major index for the analysis along with parameters such as irreversibility, mass and energy balance of the liquefaction process are calculated and compared in both processes.

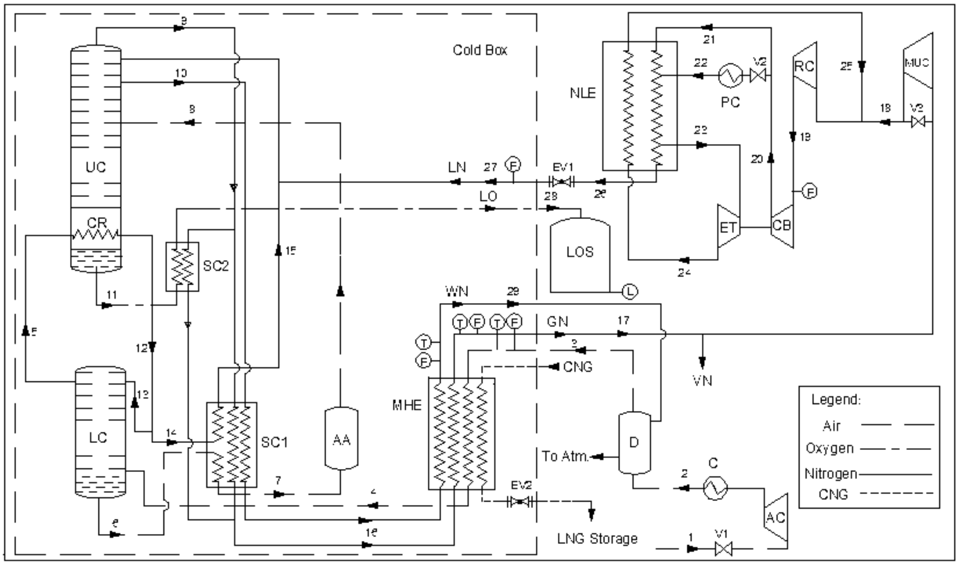
2 Industrial air separation process description

As shown in Figure 1, the dustless air enters at atmospheric pressure (stream 1) and is compressed within a three-stage centrifugal air compressor (AC) to about 4.3 bars and then it is cooled to about 10°C (stream 2). The dry air without carbon dioxide from the dryer (D) at about 17°C and 4 bars passes into the cold box MHE and is cooled to –172°C (stream 4) by MHEs outgoing streams which are gaseous nitrogen (GN) and waste nitrogen (WN). After cooling, the air passes directly into the undermost stage of the high-pressure column (lower column). The high-pressure column and low-pressure column [upper column (UC)] are thermally attached by a condenser/re-boiler. The lower column has 11 stages and the UC has 14 stages. A pressure drop of 0.01 bar is measured for each stage. The air is separated into nitrogen-rich (stream 5) and oxygen-rich streams (stream 6) which are fed to the UC. The oxygen-rich liquid from the bottom of the lower column (stream 6) is sub-cooled in the sub-cooler 1 (SC1) and is filtered through acetylene absorber (AA) and then passed to the middle of the UC (stream 8) where it is separated into a nitrogen stream from the top (stream 9) and liquid oxygen (LO) stream from the bottom (stream 11) and a WN stream from an intermediate point (stream 10).

The pure LO in the bottom of the UC will boil at a lower temperature than the condensing point of the nitrogen enriched air in the top of the lower column. This exchange of heat takes place in the condenser re-boiler (CR) and thus provides the oxygen vapour boil-up in the UC as well as the LN reflux back into the lower column (stream 13). A part of the LN reflux coming back to the lower column from the CR is diverted through the sub cooler (stream 14) and then passed into the top of the UC to provide reflux (stream 15). Cooling the process is provided by adding LN from the nitrogen liquefier section to the top of the UC (stream 27).

The GN stream at close to atmospheric pressure from the air separation cold box enters the nitrogen makeup compressor (MUC) and is compressed to about 4.5 bars (stream 18). This compressed nitrogen is mixed with the coming stream from the nitrogen liquefaction box (stream 25) and is compressed to a pressure about 31 bars in the recycle compressor (RC) and enters the compressor brake (CB) of the expansion turbine (ET). This nitrogen is compressed to a pressure about 37 bars (stream 20) and most of the stream enters the nitrogen liquefaction exchanger (NLE). The rest of it passes to the Freon refrigeration (pre-cooler) and after being cooled to about –30°C enters the liquefaction exchanger (stream 22).

Figure 1 Industrial ASU flow sheet including CNG



The nitrogen entering the liquefier exchanger is cooled by expanded nitrogen (stream 24) leaving the ET. The nitrogen stream again divides at the cold end of the liquefier exchanger. A part of the nitrogen (stream 23) is expanded in the ET to a pressure and temperature about 4.5 bars and –160°C, respectively. The work generated in the ET is used to drive the compressor. The unexpanded portion of the nitrogen (stream 26) is passed through expansion valve (EV1) and then is fed into the top of the UC as LN (stream 27).

WN stream after being warmed in the main exchanger is used for dryer regeneration. The LO is withdrawn from the bottom of the UC and after being sub-cooled (SC2) enters into the liquid oxygen storage (LOS).

3 Combined air separation and natural gas liquefaction process

As shown in Figure 1, for producing LNG in this ASU the pre-treated CNG with methane composition is assumed to enter into the warm end of the MHE at a pressure of 5.0 MPa and a temperature of 37°C (Lim et al., 2014) and is cooled with cold streams (WN and GN) and then is sent to storage as LNG at a pressure of 150 kPa. Liquefying CNG requires additional cooling in the ASU and this cooling is provided in the MHE. In this ASU, the ambient temperature is important and it is effective on LNG production. The temperature of WN and GN streams after main exchanger are actually lower than the ambient temperature (heat is transferred from ambient to these streams, after leaving the MHE), thus the limitation of these streams' temperature is ambient temperature. The ambient conditions are 25°C temperature and 101.325 kPa pressure with a relative humidity of 60%.

4 Thermodynamic analysis

4.1 Mass and energy balance

To analyse the performance of the proposed industrial ASU, the mass flow rate of streams into the cold box are calculated. These streams are not pure substances (i.e., GN stream is a mixture of oxygen and nitrogen), so a MATLAB program employing gradient descent method (Rumelhart et al., 1986) is used for the calculation of streams mass flow rate. The equations (1)–(5) are governing equations for steady state mass balance procedure (Wark, 1995). Where $\dot{m}_{LO}$, is LO mass flow rate and P_1, P_2, P_3 are nitrogen percent and P_4, P_5, P_6 are oxygen percent in LO, vent nitrogen (VN) and WN, respectively. The amounts of $\dot{m}_{WN}$ and $\dot{m}_{VN}$ are calculated according to gradient descent method. The mass balance procedure ends when the amounts of $\dot{m}_{N_2}$ and $\dot{m}_{N_2,theo}$ in equations (4) and (5) are almost equal. The theoretical dry air is assumed a mixture of oxygen and nitrogen with the mass ratio of 3.31406 as mentioned at equation (5).

$$\dot{m}_{air} = \dot{m}_{O_2} + \dot{m}_{N_2} \tag{1}$$

$$\dot{m}_{VN} = \dot{m}_{GN} - \dot{m}_{LN} \tag{2}$$

$$\dot{m}_{O_2} = \dot{m}_{LO} \cdot P_4 + \dot{m}_{VN} \cdot P_5 + \dot{m}_{WN} \cdot P_6 \tag{3}$$

$$\dot{m}_{N_2} = \dot{m}_{LO} \cdot P_1 + \dot{m}_{VN} \cdot P_2 + \dot{m}_{WN} \cdot P_3 \tag{4}$$

$$\dot{m}_{N_2,theo.} = 3.31406\, \dot{m}_{O_2} \tag{5}$$

The energy balance can be used to determine GN and LN mass flow rate ($\dot{m}_{GN}$ and $\dot{m}_{LN}$). The process is steady state and steady flow with negligible potential and kinetic energy effects. The cold box is assumed adiabatic with no external work, so the energy balance (Wark, 1995) for the cold box of ASU in Figure 1 is given as:

$$\dot{m}_{air} h_{air} + \dot{m}_{LN} h_{LN} = \dot{m}_{GN} h_{GN} + \dot{m}_{WN} h_{WN} + \dot{m}_{LO} h_{LO} \tag{6}$$

The energy balance for the cold box of combined unit is given as:

$$\dot{m}_{air} h_{air} + \dot{m}_{LN} h_{LN} + \dot{m}_{CNG} \left(h_{CNG} - h_{LNG} \right) = \dot{m}_{GN} h_{GN} + \dot{m}_{WN} h_{WN} + \dot{m}_{LO} h_{LO} \tag{7}$$

4.2 Exergy analysis

The definition of thermo-mechanical exergy (ψ_{tm}) is a work resulted in a reversible process from initial state (T, P, h) to the final environmental state (T_0, P_0, h_0), while the definition of chemical exergy (ψ_{ch}) is a work resulted in a reversible process from initial state (T_0, P_0, h_0) to the final environmental components state (T_0, P_{00}, h_{00}) (Kotas, 1995). So, the total exergy would be (Wark, 1995):

$$\psi_{tot} = \psi_{tm} + \psi_{ch} \tag{8}$$

In this study, exergy analysis is applied to define unit effectiveness and the irreversibility that occurs within the cold box of the ASU and is compared to the case with added CNG to the cold box.

The exergy efficiency of the process is defined as the ratio of the useful exergy to input exergy:

$$\varepsilon = \frac{useful\ exergy\ out}{exergy\ in} \tag{9}$$

For ASU in this operating condition, only LO is produced therefore, the effectiveness is calculated as:

$$\varepsilon = \frac{\Psi_{tot,L}}{\dot{W}_{tot,unit} + \Psi_{tot,air}} \tag{10}$$

where $\Psi_{tot,LO}$, is the total exergy of the LO, $\Psi_{tot,air}$ is the total exergy of the inlet air and $\dot{W}_{tot,unit}$ is the total electric energy of the ASU. For combined unit, effectiveness is calculated as:

$$\varepsilon = \frac{\Psi_{tot,LO} + \Psi_{tot,LNG}}{\dot{W}_{tot,unit} + \Psi_{tot,air} + \Psi_{tot,CNG}} \tag{11}$$

where $\Psi_{tot,CNG}$ is the total exergy of the inlet CNG and $\Psi_{tot,LNG}$ is the total exergy of the produced LNG. The thermo mechanical exergy is expressed as equation (12), when the potential and kinetic energy are neglected.

$$\Delta\Psi_{tm} = \left(H_o - H_i\right) - T_0\left(S_o - S_i\right) \tag{12}$$

where $\Delta\Psi_{tm}$, is change of exergy between the initial and the final states of the system, T_0 is the ambient temperature and H_o, and S_o represent the enthalpy and entropy of the outlet stream. H_i and S_i represent the enthalpy and entropy of the inlet stream, respectively.

In this study WN and VN streams are transferred to atmosphere and LOS tank is in atmospheric pressure, so chemical equilibrium in the environment is used as base of exergy analysis. Total exergy of streams (air, WN, GN, LO, LN, CNG and LNG) are given as below.

The equation for ψ_{tot} on a unit mass of dry air basis is as below (Wark, 1995):

$$\begin{aligned}\psi_{tot} &= \left(c_{p,a} + \omega c_{p,v}\right)\left(T - T_0 - T_0 \ln\frac{T}{T_0}\right) + (1+\varpi)R_a T_0 \ln\frac{P}{P_0} \\ &+ R_a T_0\left[(1+\varpi)\ln\frac{1+\varpi_{00}}{1+\varpi} + \varpi \ln\frac{\varpi}{\varpi_{00}}\right]\end{aligned} \tag{13}$$

where $c_{p,a}$, $c_{p,v}$, R_a, ω, ϖ are specific heat of air, specific heat of water vapour, specific gas constant for dry air, specific humidity (mass ratio), specific humidity (mole fraction ratio), respectively. The total stream exergy for an ideal-gas mixture per mole of the mixture is (Wark, 1995):

$$\psi_{tot} = \sum_{i=1}^{n} y_i\left[h_{i,T} - h_{i,T_0} - T_0\left(s_{i,T}^0 - s_{i,T_0}^0\right)\right] + R\,T_0 \ln\frac{P}{P_0} + R\,T_0 \sum_{i=1}^{n} y_i\left(\ln\frac{y_i}{y_{i,00}}\right) \tag{14}$$

where y_i is mole fraction, h_i and s_i^0 are enthalpy and absolute entropy, R represents the ideal gas constant and the amounts of $y_{i,00}$ is 0.7662 and 0.2055 for O_2 and N_2, respectively, for φ = 60%. The total exergy for WN and GN streams is calculated according to equation (14). The total exergy for LN and LO streams is calculated as below (Wark, 1995):

$$\psi_{tot} = \sum_{i=1}^{n} y_i \left[h_{i,T} - h_{i,T_0} - T_0 \left(s_{i,T} - s_{i,T_0} \right) \right] + RT_0 \sum_{i=1}^{n} y_i \left(\ln \frac{y_i}{y_{i,00}} \right) \tag{15}$$

The exergy of CNG and LNG are formulated as the following:

$$\psi_{tot} = \psi_{tm} + \psi_{ch} = \sum_{i=1}^{n} y_i \left(\mu_i - \mu_{i,00} \right) \tag{16}$$

where

$$\psi_{tm} = \sum_{i=1}^{n} y_i \left(\mu_i - \mu_{i,0} \right) \tag{17}$$

$$\psi_{ch} = \sum_{i=1}^{n} y_i \left(\mu_{i,0} - \mu_{i,00} \right) \tag{18}$$

$$\mu_i = h_i - T_0 s_i \tag{19}$$

The irreversibility of cold box is defined by exergy balance. The process is steady state and steady flow with negligible potential and kinetic energy effects. The cold box is assumed adiabatic with no external work, therefore the exergy balance for ASU is given as:

$$\dot{I}_{cv} = \left(\dot{m}\psi \right)_{air} + \left(\dot{m}\psi \right)_{LN} - \left(\dot{m}\psi \right)_{GN} - \left(\dot{m}\psi \right)_{WN} - \left(\dot{m}\psi \right)_{LO} \tag{20}$$

And for combined unit it is as bellow:

$$\dot{I}_{cv} = \left(\dot{m}\psi \right)_{air} + \left(\dot{m}\psi \right)_{LN} + \left(\dot{m}\psi \right)_{CNG} - \left(\dot{m}\psi \right)_{LNG} - \left(\dot{m}\psi \right)_{GN} - \left(\dot{m}\psi \right)_{WN} - \left(\dot{m}\psi \right)_{LO} \tag{21}$$

The calculation of streams energy, exergy, irreversibility and process effectiveness have been done using equations (6)–(21) by experimental data and the aid of a data processing program.

5 Experiment procedure

Experimental analysis is presented on an industrial ASU in four cases. The variable parameter in these cases was the mass flow rate of AC ($\dot{m}_{air}$). As shown in Figure 1, the mass flow rate of AC is controlled with inlet valve of AC (V1). This parameter has a direct effect on system operation due to influence on LN (unit cooling capacity) mass flow rate and LO mass flow rate. Each case has been repeated three times and the average amounts of the results are considered. By changing $\dot{m}_{air}$ the results have been recorded after the unit is in steady state condition. The ambient condition in the tests are almost the same at each time intervals. The results are shown in Tables 2–5.

Table 1 Specific irreversibility comparison

i (kJ/kg)	*Case I*	*Case II*	*Case III*	*Case IV*
Actual ASU	59.2	61.2	68.2	67.3
Modified ASU	59.4	61.7	68.9	67.6
Combined unit	55	55.2	62.2	64

Table 2 Experimental data case I ($\dot{m}_{air}$ = 1,846.7 kg/h)

Material (i)	*Stream*	*T°C*	*P kPa*	*VF*	y_{N_2} *kmol/kmol*	y_{O_2} *kmol/kmol*	$\dot{m}$ *kg/h*	Ψ_{tot} *kJ/kg$_i$*
Air	3	29.5	401.3	1	0.791	0.209	1,846.7	121.9
GN	17	20.3	121.3	1	0.98	0.02	554.5	33.1
WN	29	6	121.3	1	0.965	0.035	1,379.9	30.7
LN	27	-	353.3	0	0.98	0.02	461	703.7
LO	28	-	101.3	0	0.007	0.993	373.3	738.9

Table 3 Experimental data case II ($\dot{m}_{air}$ = 1,887.9 kg/h)

Material (i)	*Stream*	*T°C*	*P kPa*	*VF*	y_{N_2} *kmol/kmol*	y_{O_2} *kmol/kmol*	$\dot{m}$ *kg/h*	Ψ_{tot} *kJ/kg$_i$*
Air	3	19.9	411.3	1	0.791	0.209	1,887.9	125.4
GN	17	10.6	121.3	1	0.967	0.033	728.3	30.8
WN	29	–1.1	121.3	1	0.947	0.053	1,239.3	28.5
LN	27	-	361.3	0	0.967	0.033	433	699.1
LO	28	-	101.3	0	0.004	0.996	353.3	739.6

Table 4 Experimental data case III ($\dot{m}_{air}$ = 2,015.1 kg/h)

Material (i)	*Stream*	*T°C*	*P kPa*	*VF*	y_{N_2} *kmol/kmol*	y_{O_2} *kmol/kmol*	$\dot{m}$ *kg/h*	Ψ_{tot} *kJ/kg$_i$*
Air	3	21.7	401.3	1	0.791	0.209	2,015.1	121.9
GN	17	12.1	116.3	1	0.963	0.037	650.4	26.4
WN	29	0.83	116.3	1	0.92	0.08	1,453.1	20.2
LN	27	-	354.3	0	0.963	0.037	415.1	699.2
LO	28	-	101.3	0	0.003	0.997	326.7	739.8

The temperature and pressure of streams are measured with PT 100 (T) and pressure gauge (P) devices with 0.1% and 0.5% uncertainty, respectively. The LO mass flow rate is calculated with weighting indicator device, the load cells (L) are placed at the bottom of LO tank with an uncertainty of 1.4 kg. Stream composition is considered as mole fraction of oxygen and nitrogen mixture and it is measured with oxygen analyser with 0.6% uncertainty. The total unit energy consumption in each case is measured with an electric energy metering device with 0.3% uncertainty.

Table 5 Experimental data case IV ($\dot{m}_{air}$ = 2,037.8 kg/h)

Material (i)	*Stream*	*T°C*	*P kPa*	*VF*	y_{N_2} *kmol/kmol*	y_{O_2} *kmol/kmol*	$\dot{m}$ *kg/h*	Ψ_{tot} *kJ/kg*$_i$
Air	3	29.2	421.3	1	0.791	0.209	2,037.8	126.4
GN	17	20.4	121.3	1	0.979	0.021	860.3	32.9
WN	29	9.6	121.3	1	0.89	0.11	1250	22.2
LN	27	-	341.3	0	0.979	0.021	379.2	706.1
LO	28	-	101.3	0	0.002	0.998	306.7	740.5

6 Combined unit consideration

A comparison of cold box irreversibility is accomplished between actual ASU, modified ASU (an actual ASU that WN and GN streams temperature increased to about ambient temperature) and combined unit.

The results are shown in Table 1 for four operating conditions. The results indicates that the cold box irreversibility increased in modified ASU due to increase of temperature difference in all operating conditions, while it decreased in combined unit. So, the effectiveness of combined unit is greater than modified ASU. For this reason, the application of CNG in actual ASU is preferred.

7 Results and discussion

7.1 Experimental results and discussion

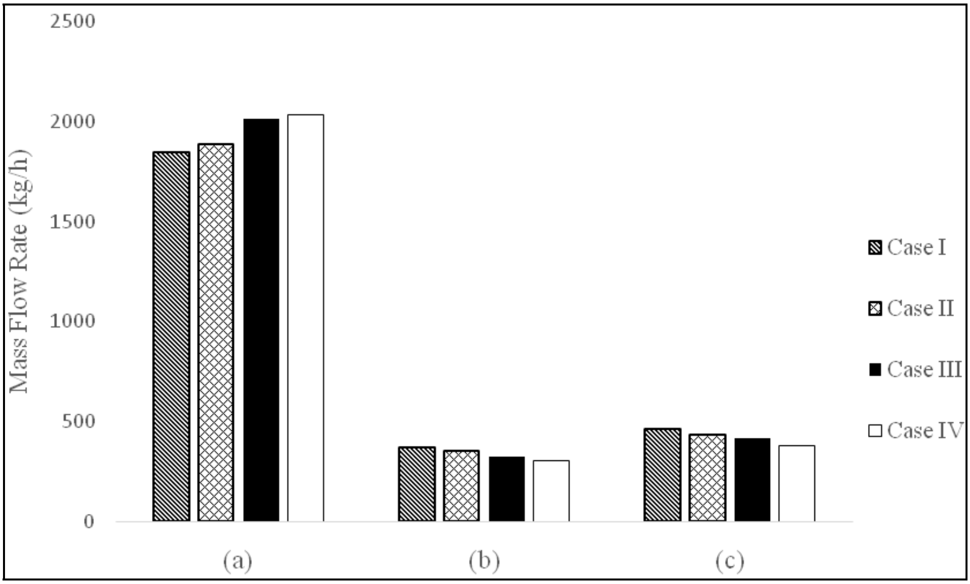
Experimental results on the ASU are presented in Tables 2–5, where y_{N_2} and y_{O_2} are composition (purity) of mentioned streams, VF is its vapour fraction and (ψ_{tot}) is the amount of total exergy of each stream which is calculated according to equations (13) to (15). The operating point of the air mass flow rate of this industrial ASU is about 2,000 kg/h of dry air, therefore, it has been changed in the limit of 1,846–2,038 kg/h. The total unit energy consumption in each case is presented in Table 6.

Table 6 Total unit energy consumption

$\dot{W}_{tot,unit}$ *(kW)*	*Case I*	*Case II*	*Case III*	*Case IV*
ASU	893	921.3	955.7	927

The mass flow rate of air, LN and LO of each case is shown in Figure 2. By increasing the mass flow rate of AC, LN mass flow rate reduces (cooling of the process is provided by LN mass flow rate) therefore, the LO mass flow rate decreases. Increasing the air mass flow increases the feed stream to the columns and it causes them to warm up thus the mass flow rate of LN and continually the LO mass flow rate reduces.

Figure 2 Comparison of operating cases I–IV, (a) air mass flow rate (kg/h) (b) LO mass flow rate (kg/h) (c) LN mass flow rate (kg/h)



7.2 Theoretical results and discussion

If the ambient temperature increases, then the possibility to liquefy CNG will increase, and vice versa, as shown in Figure 3. This is due to reducing outlet availability of streams. The Ambient temperature has a direct effect on the enthalpy of WN and GN streams so, according to first law of thermodynamic the amount of LNG production changes in different seasons. This is the limitation of LNG production in low ambient temperatures.

Table 7 LNG production for 1 kg/h dry air

	Case I	*Case II*	*Case III*	*Case IV*
LNG (kg/h)	0.019	0.027	0.026	0.013

The amount of LNG production for 1 kg/h dry air in ASU for operating conditions I–IV is shown in Table 7. As the results show, the amount of LNG production for natural gas specifications and ambient conditions mentioned in Section 3 are about 0.013–0.027 kg/h for operating conditions of cases I–IV of ASU.

The irreversibility of cold box is calculated according to equations (20) and (21) and it is shown in Figure 4(a). In all operating conditions this quantity decreases about 5–11% in combined unit compared with ASU. The reduction of irreversibility is due to internal temperature difference decrease in the cold box. Air mass flow rate has a direct effect on irreversibility, therefore, increasing the air mass flow rate increases the irreversibility of cold box. In combined unit some of the lost exergy is enhanced by liquefying CNG hence the irreversibility of the combined unit is lower than ASU.

Figure 3 LNG production in different operating conditions versus ambient temperature

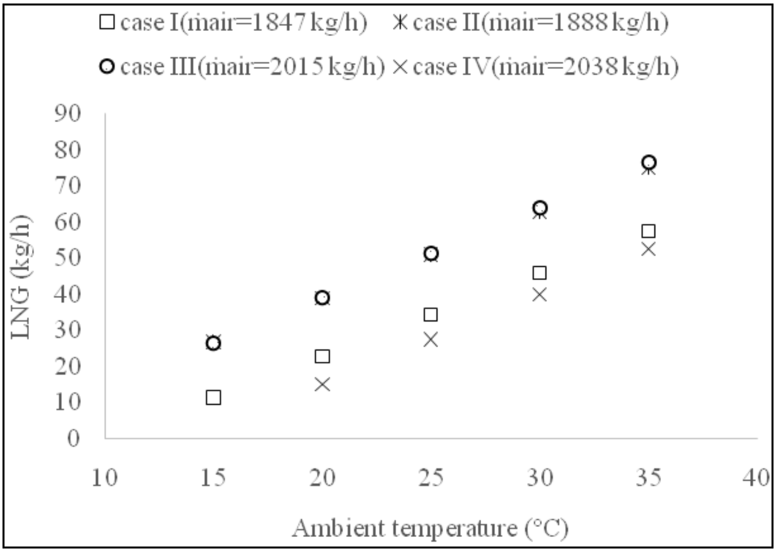
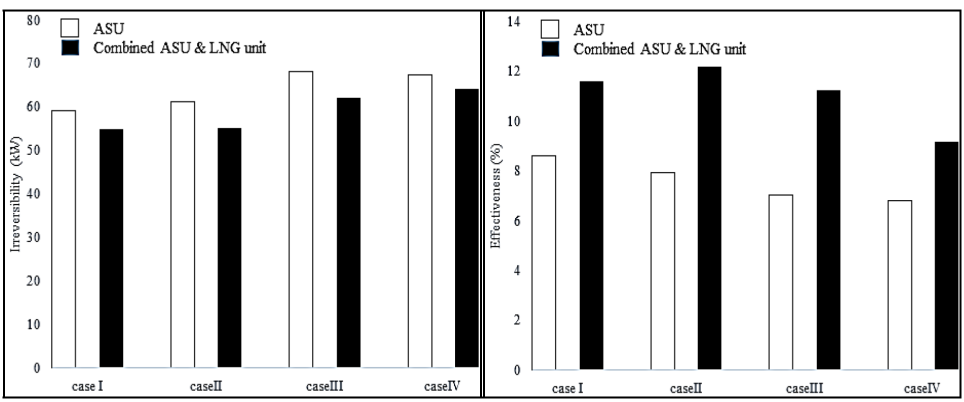


Figure 4 (a) Cold box irreversibility comparison of ASU and combined unit in different operating conditions (b) Effectiveness comparison of ASU and combined unit in different cases (see online version for colours)



(a) (b)

According to equations (10) and (11), process effectiveness in combined unit and ASU is calculated. The results are shown in Figure 4(b). Effectiveness has a reverse relation with irreversibility, and it reduces while irreversibility increases. Therefore, the effectiveness of the combined unit is higher than ASU. The results indicate that the effectiveness in combined unit is about 35–60% greater than ASU in all operating conditions.

8 Conclusions

In combined ASU and LNG units LNG can be obtained during gas or LO production. For liquefying natural gas in an ASU, additional cooling is required so that the LO production of the unit is not changed. This cooling is provided in the MHE of the ASU cold box. The limitation temperature for WN and GN streams is the ambient temperature. In combined unit the results have indicated a reduction of about 5–11% in the irreversibility of cold box and an increase of about 35–60% in the effectiveness of the combined unit. The amount of LNG produced in this combined unit for 1 kg/h dry air at standard conditions is about 0.013–0.027 kg/h for different cases and the amount of LO production is about 0.15–0.2 kg/h. Since this process has been able to produce LNG while LO is produced, then it is a good option for small scale liquid natural gas production. So, the advantages of this process are multipurpose production besides unit effectiveness growth. Factors such as operability and safety must be considered.

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Nomenclatures

c_p	Specific heat (kJ/kg K)
h	Specific enthalpy (kJ/kg)
i	Specific irreversibility (kJ/kg)
$\dot{m}$	Mass flow rate (kg/h)
P	Pressure (kPa)
P	Purity (%)
R	Universal gas constant (kJ/kmole K)
s	Specific entropy (kJ/kg K)
T	Temperature (K)
y	Mole fraction (%)
Greek symbols	
ε	Effectiveness
μ	Chemical potential
φ	Relative humidity
ψ	Exergy
ω	Humidity

Nomenclatures (continued)

Subscripts	
00	Environmental dead state
0	Ambient (dead state)
a	Air
act	Actual
ch	Chemical
i	Entrance
o	Exit
tm	Thermo mechanical
theo	Theoretical
tot	Total
v	Vapour