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Sensitivity Analysis of Simple Expander– Nitrogen and Two Expander – Nitrogen Liquefaction Processes of Natural Gas

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Abstract: The sharp seasonal fluctuations in gas consumption in the domestic sector and prioritizing this segment have led to serious gas supply problems in other subdivisions, such as power plants during cool seasons. One of the approaches presented in this field is storing liquefied natural gas in warm seasons and using it during the colder seasons to supply the power required for power plants. In this regard, processes were selected based on the capacity required for storing liquefaction units over a 200-day period for a commonly combined cycle power plant with a power generating capacity of 332 MW. In this study, the simple expanders – nitrogen and two expander – nitrogen liquefaction processes have been evaluated. Changes in environmental and operating conditions (such as changes in discharge, pressure, temperature, and composition percentage of natural feed gas components) are problems that peak shaving units will face permanently. As a result, low sensitivity to changing conditions is one of the important criteria in choosing the right process. In this study, the dimensionless sensitivity analysis method was used to study the behavior of liquefaction cycles. The results show that the simple expander – nitrogen process has a higher power consumption. The sensitivity to changing environmental and operating conditions for the two-expander process is 70% lower than that of the simple expander – nitrogen process. Also, the uncertainty in power consumption overall values is 2.58% for the simple expander – nitrogen process and 1.14% for two expander – nitrogen process.

keywords: Simple Expander – Nitrogen Process, Two Expander – Nitrogen Process, Sensitive Analysis, Environmental and Operating Conditions

1. Introduction

Natural gas is among the cleanest fossil fuels, with a rising replacement demand with other fossil fuels. With Iran ranked second in the world in terms of natural gas resources, government authorities have always sought to make natural gas available to consumers in every home, industry and power sector. One way of transporting natural gas from the extraction and processing location to its consumption site is to use gas transmission lines. Since gas transmission via pipelines in distances less than 3,000 km requires lower investment and operational costs, less technical knowledge, and involves a reduced amount of complexity than other methods (such as natural gas and petroleum liquefaction), this method has been used in most countries around the world, including Iran (Mokhatab et al., 2013).

Due to the availability of abundant natural gas resources in Iran and its cleaner combustion products in comparison to other fossil fuels (less greenhouse gas emissions), the use of gas has always been emphasized as the main fuel for Iran's power plants. Although gas transmission through pipelines is a simple and low cost, increasing domestic gas consumption in the cold seasons causes power plants to cut down on the demand for power in gas transmission and distribution lines during peak household consumption. This forces alternate fuel use during the cold, such as petrol and diesel, which has more environmental pollutants and compensation for the costs that they incur is a huge cost to the government. An operational solution to avoid this problem is to have surplus natural gas stored near power plants during periods of low demand (during warm seasons). The ratio

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of energy to natural gas volume is extremely low at ambient pressure and temperature, therefore, storing natural gas in a regular gaseous form occupies a large space. Therefore, the volume needs to be reduced in some way. The most economical and common method in the world is to lower the temperature of natural gas until it is liquefied (about -161 degrees Celsius), resulting in approximately one-sixth of the initial volume at atmospheric pressure (Mokhatab et al., 2013).

Natural gas is mainly methane (over 90% in volume), the hydrocarbon having the highest heat value, and the rest being ethane and propane; thus, it is used as a clean fuel (whether it's a Compressed Natural Gas (CNG) or a Liquefied Natural Gas (LNG)). The advantage of natural gas as a fuel is that it burns cleanly and with minimal CO and other hydrocarbon emissions. It is also used as a part of fertilizers as well as chemical and petrochemical production processes. The biggest drawback of natural gas is that it is very light, so it needs to be compressed up to 250atm to be used as CNG, while LNG can be stored and transported at a much lower pressure (60-80atm), which has been proven to be executable, though it requires proper insulation. The normal boiling point of natural gas is-162°C (or 111 K), therefore it requires cryogenic liquefaction along with a special design consideration to minimize silent boiling and maintain safety during storage. However, according to an inaccurate estimate, liquefied natural gas is only economically viable for long-distance transportation and the minimum covered distance should be at least 2500 km. LNG is transported across countries and even continents in the pipelines on land or boarded on ships. In terms of cooling, natural gas liquefaction processes can be divided into three main groups: cascading liquefaction process, multi-component cooling liquefaction process, and expander liquefaction process (Mukhopadhyay, 2010).

Sanavandi et al concluded that the sensitivities of two liquefied natural gas (LNG) cycles, single mixed refrigerant (SMR) and propane pre-cooled mixed refrigerant (C3MR) to input variables are investigated and compared using normalized sensitivity analysis. The normalized sensitivity coefficients indicate the output of the cycles, specific energy consumption (SEC) is more sensitive to the inlet temperature and pressure of the mixed refrigerant compressors, the mixed refrigerant composition and the discharge temperature of the after coolers (Sanavandi, Mafi, & Ziabasharhagh, 2019).

Abdul Qyyum and Duong concluded that the dual mixed refrigerant (DMR) liquefaction process is complicated and sensitive compared to the competitive propane pre-cooled mixed refrigerant liquefied natural gas (LNG) process. The required energy is significantly influenced by the variations in the variables in the cold mixed refrigerant (approximately 63%), while changes in the warm mixed refrigerant (WMR) section only slightly affect the uncertainty of the required specific energy (Abdul Qyyum, & Duong, 2019).

Ghorbani and Shirmohammadi concluded that utilizing an absorption refrigeration system as an alternative to the compression refrigeration system of the MFC refrigeration cycle in an integrated superstructure with the main aim of reduction in required energy is investigated. Exergy analysis shows that the highest exergy destruction is imposed by after-burner with the amount of 33.91% and the lowest exergy destruction is occurred in the valves by the amount of 0.83%. The presented integrated structure has overall thermal efficiency (LHV Base) of 70.56%, and the Specific power of 0.162 kWh/kg LNG (Ghorbani, & Shirmohammadi, 2018).

Manghalsaz et al concluded that the cost of annual investment in the entire cryogenic cycle of the two expander – nitrogen process was 28% lower compared to the simple expander – nitrogen process. Also, the exergy efficiency of the whole cryogenic cycle is 3% higher in the two expander – nitrogen process than in a simple expander – nitrogen process (Manghalsaz, Mousavi, & Mafi, 2016).

Moradi et al concluded that the non-dependent two expander – nitrogen process is a good substitute for the simple expander – nitrogen process, which in addition to retaining superior properties, has improved performance indicators such as power consumption and specific work (Moradi, Khanki, & Mafi, 2015).

After modeling both the expander – nitrogen process and mixed refrigerant processes and optimizing them, Moradi et al investigated their power consumption and their results showed that the power consumption of a liquefaction unit using the mixed refrigerant process has an approximately 0.6 similar power consumption unit that uses the expander – nitrogen process. This indicates the superiority of the mixed refrigerant process over the expander process in power consumption and other thermodynamic parameters such as specific work and thermal efficiency. Another result is that the mixed refrigerant process is more sensitive to changes in environmental and operating conditions than the simple expander – nitrogen process (Moradi, Mafi, & Khanaki, 2015).

Li et al concluded that the optimization of large-scale gas liquefaction by optimizing the thermodynamic design based on a genetic algorithm. With some assumptions, the results of this simulation showed a high liquefaction energy efficiency ratio (52% for hydrogen and 58% for nitrogen and methane). Furthermore, significant energy efficiency was achieved by applying a cooling turbine instead of a pressure-reducing valve (Li, Wang, & Ding, 2012).

One of the important parameters in the proper selection of the natural gas liquefaction process is the study of process sensitivity to changes in its environmental and operating conditions, which has been neglected in previous researches available in this field. Given the frequent variations in environmental (such as ambient temperature) and operating conditions (such as pressure disturbances in distribution pipelines and composition percentages of natural feed gas components as well as possible uncertainties due to the measurement-equipment errors), the need for a comprehensive study to properly select the natural gas liquefaction cycle for storing gas in the vicinity of power plants is becoming increasingly evident. While examining and studying liquefaction processes, it should be noted that proper and appropriate cycle selection will depend on the identification of key liquefaction cycle parameters and a proper understanding of the behavior of these parameters in relation to their environmental and operational changes. Therefore, in this research, the behavioral study of natural gas liquefaction cycles is considered by using a peak shaving to store gas in the vicinity of power plants, considering the environmental and operational conditions of Iran's gas distribution lines. The sensitive analysis is a useful tool for identifying key parameters of a system and examining their behavior in relation to changes in environmental and operating conditions (Qureshi, & Zubair, 2006), which is considered in this study.

2. Descriptions of the Studied Liquefaction Processes

In this study, both simple expander – nitrogen and two expander – nitrogen processes were selected, and necessary analyses were performed to identify the behavior of the performance parameters. The main reasons for choosing these two processes were the simplicity of their cycles' structures, their structural similarity (for final comparison), and the operationalization of their use in different countries for natural gas storage (Mokhatab et al., 2013).

2.1. The Simple Expander – Nitrogen Process

This process also called the inverted Brighton cycle, is the simplest type of expander process. The used cooling agent in this cycle is nitrogen and the cooling required to liquefy natural gas is provided during an expansion process at the expander. This process is also associated with the production of work. Simplicity in operation, shorter start-up time, and high safety and low equipment are features of this process (Chang et al., 2012). High power consumption and as a result, low efficiency, is the biggest drawback of this process, which makes it more suitable for small scale and peak shaving units (Chang et al., 2012). In this process, the temperature-drop and, thus, the cooling generation is due to the close expansion to the cooling agent's constant entropy of the expander. Figure 1 shows the schematic diagram of the natural gas liquefaction process by the simple expander – nitrogen method.

2.2. The Non-Dependent Two Expander – Nitrogen Process

The two expander – nitrogen cryogenic process uses two closed refrigeration cycles to pre-cool and liquefy the natural gas. The cooling fluid used in both cycles is nitrogen. In this process, the temperature-drop and consequently the cooling generation is due to the close expansion to the cooling agent's constant entropy of the expander. Figure 2 shows the schematic diagram of the natural gas liquefaction process by the two expander – nitrogen method.

2.3. Determining the Capacity of the Studied Liquefaction Units

The cycles studied in this study are the simple expander – nitrogen and the two expander – nitrogen processes. The liquefaction capacity of these processes has been calculated for a 332 MW common combined cycle power plant in Iran. The details of capacity determination are given in Table 1.

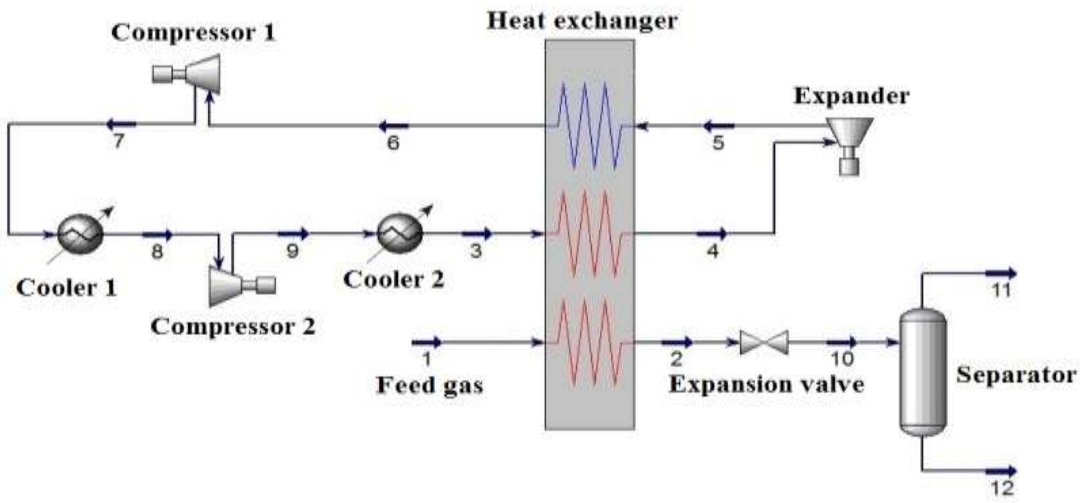

Figure 1. Simple expander – nitrogen natural gas liquefaction process

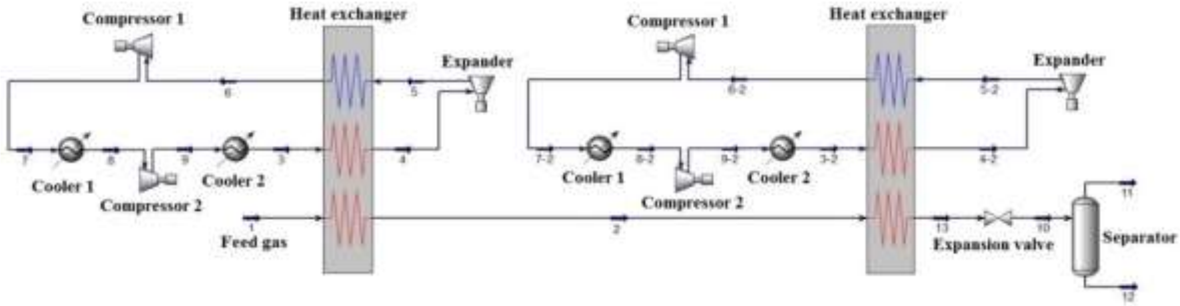

Figure 2. Two expander – nitrogen natural gas liquefaction process

Table 1. Determining the capacity of the studied liquefaction units

	Value	Description
Power	323 MW	Combined cycle unit of karaj power plant
Thermal efficiency	45.4%	Extracted from the statistics of the Iranian electricityindustryin2013 (http://amar.tavanir.org.ir,2015)
Heat power required	732 MW	
Number of Days of Power Plant Operation	Sixty days	The peak period of consumption (cold period) is as summed to be 60 days.
Thermal value of gas	36664 kJ/m³	Extracted from the statistics of the iranian electricity industry in 2013 (http://amar.tavanir.org.ir,2015)
The amount of gas needed for the peak period	103,000,000 m³	
Coefficient of change in LNG volume	600	Reducing the volume of the gas when it comes to liquid. . (Mokhatab et al.,2013)
The amount of LNG required for the peak period(volume)	172000 m³	
LNG density	470 kg/m³	. (Mokhatab et al., 2013)
The amount of LNG required for the peak period(mass)	81000 tons	
Number of days predicted for LNG production	200 days	(Venkatarathnam., 2018)
LNG production per day	405 tons per day	
LNG production unit capacity	147000 tons per year	

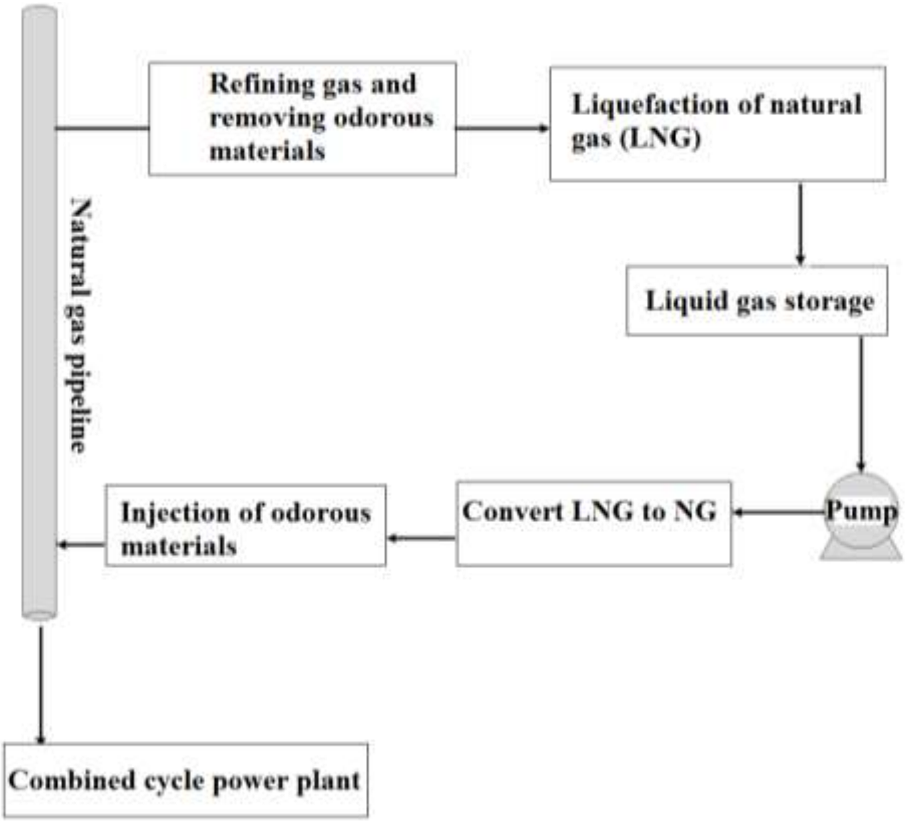

Figure 3. Schematic of the natural gas liquefaction unit and the combined cycle power plant

2.4. Inlet Feed Gas Properties

The pressure and temperature of the feed gas inlet to the liquefaction section are considered 60 bar and 32°C, respectively (Aspelund et al., 2010). Regarding the percentage of the feed gas composition to the liquefaction unit, it is important to note that no liquefaction unit has been established in Iran, so direct access to accurate information on natural gas composition after pretreatment operations (combining inlet feed gas into the liquefaction unit) is not available. Gas pretreatment is an operation that must be carried out before the natural gas enters the liquefaction unit during which impurities in the gas such as water, carbon dioxide, hydrogen sulfide, and heavy hydrocarbon elements are removed or reduced to minimal levels, to prevent corrosion of equipment and clogging of pipelines in the liquefaction unit (Mokhatab et al., 2013). It should be taken into account that the permissible levels of impurities depend on the technology of the liquefaction unit (www.nigc.ir). Table 2 presents the results of various analyses on the percentage of natural gas composition in the Tehran Gas Distribution Pipelines (www.nigc.ir). As can be seen, the percentages of natural gas composition in the different analyses are different, and no one-percent constant composition can be considered for the natural gas in the distribution pipelines.

Frequent changes in the gas composition percentage in the nation's gas distribution pipelines are one of the most important parameters to consider when selecting peak shaving liquefaction units. In this study, by categorizing the information provided in internal sources on the percentage of natural gas composition prior to the pretreatment operation (Zargar et al., 2009) as well as gathering information provided by external sources on the percentage of natural gas composition after the pretreatment operation, and also considering the relatively good agreement between the results of the first analysis and the information provided in the reference (Venkatarathnam., 2008), the percentage of feed gas composition at the inlet of the liquefaction unit is assumed as portrayed in Table 3.

Table 2. Different analysis of percent composition of Tehran gas distribution line (www.nigc.ir)

Natural gas components	Analyze1	Analyze2	Analyze 3
Methane (mol%)	86.8-93.1	90-92	88-89
Ethane (mol%)	1.1-5.3	2.5-3.5	4-4.4
Propane (mol%)	0.3-1.7	0.2-0.8	1.1-1.6
Butane (mol%)	0.2-0.6	0.1-0.5	0.6-0.8
Heavy hydrocarbons (mol%)	0.1-0.5	0.2-0.4	0.4-0.5
Nitrogen (mol%)	2.7-5.8	2.7-5.8	3.3-3.7
Carbon dioxide (mol%)	0.1-1.4	1-1.3	1.3-1.5
Hydrogen sulfide (mg/sm_3)	0.1-3	0.4-1	very little
Mercaptan (mg/sm_3)	0.3-13.3	1.6-15	very little
Sulfur (mg/sm_3)	5.4-20.5	5-25	-
Water (mg/sm_3)	0.5-23	-	-

Table 3. Percentage composition of inlet gas to liquefaction unit (Venkatarathnam., 2008)

Inlet feed gas components	Molar composition percentage
Nitrogen	4%
Methane	87%
Ethane	5.5%
Propane	2%
n-Butane	0.5%
i-Butane	0.5%
i-Pentane	0.5%

3. Modeling and Simulations

In this study, Aspen Hysys V9 software was used to simulate the liquefaction cycles. It is considered to be an important software used in industrial and chemical process simulations and optimizations, with a proper state equation that is suitable for different applications, defining most of the required simulation elements, having control units to regulate different parts, and increasing the speed of modeling and optimization operations due to the calculations of the first law of thermodynamics (Hyprotech Ltd., 2010).

3.1. Equation of state

In this study, the Peng-Robinson equation has been used to predict the thermophysical properties of hydrocarbons and nitrogen mixtures as well as vapor-liquid phase equilibrium calculations (Mokarizadeh et al., 2010), (Remeljej, & Hoadley, 2006), (MS Khan et al, 2014). The Peng-Robinson equation of the state is a semi-empirical EOS and is a kind of state equation derived from Van der Waals EOS (Danesh, 1998). The algebraic form of this equation shown in Eq. (1) (Ahmed, 2007):

$$P = \frac{RT}{v-b} - \frac{a\alpha}{v(v+b)+b(v-b)} \quad (1)$$

In Eq. (1), a and b are constants of the equation of state, and α is the dimensionless coefficient dependent on the reduced temperature. The value of α can be obtained according to Eq. (2):

$$\alpha = \left[1 + m\left(1-\sqrt{T_r}\right)\right]^2 \quad (2)$$

In Eq. (2), $T_r$is reduced temperature. In this respect, the$m$ coefficient is defined as Eq. (3):

$$m = 0.3796 + 1.5422\omega - 0.2699\omega^2 \quad (3)$$

In Eq. (3), ω is called the acentric factor, whose values for different materials are listed in the references (Reid et al., 1987). In this study, the Hysys database was used to calculate this factor.

Thea and b coefficients in Eq. (1) are obtained using the critical point constraints known as Van der Waals's constraints (Ahmed, 2007).

These constraints at critical points are:

$$\left(\frac{\partial P}{\partial v}\right)_{T=T_c} = 0 \quad (4)$$

$$\left(\frac{\partial^2 P}{\partial v^2}\right)_{T=T_c} = 0 \quad (5)$$

If we apply these constraints in Eq. (1), the a and b coefficients will be obtained as shown in Eq. (6) and (7) (Ahmed, 2007):

$$a = \Omega_a \frac{R^2 T_c^2}{P_c} \Omega_a = 0.45724 \quad (6)$$

$$b = \Omega_b \frac{RT_c}{P_c} \Omega_b = 0.07780 \quad (7)$$

The explanations provided so far for the equation of the state were related to the prediction of pure material properties. In the case of mixtures, the above equation can be used with a mixing rule. Many mixing rules have been proposed in this study using the random mixing rule (Van der Waals mixing rule) (Ahmed, 1989). According to this rule, the$a\alpha$ and b coefficients of the Peng-Robinson equation of state shown with $(a\alpha)_m$ and $b_m$for mixtures are obtained from Eq. (8) to (10):

$$P = \frac{RT}{v - b_m} - \frac{(a\alpha)_m}{v(v + b_m) + b_m(v - b_m)} \qquad (8)$$

$$(a\alpha)_m = \sum_i \sum_j \left[z_i z_j \sqrt{a_i a_j \alpha_i \alpha_j}\left(1 - k_{ij}\right)\right] \qquad (9)$$

$$b_m = \sum_i [z_i b_i] \qquad (10)$$

In Eq. (9), the k_{ij} parameter is the material interaction coefficient parameter, whose values for the different materials are available in the Hysys software database. In this respect, z_i is the i-th component of the molar composition (He, & Ju, 2014).

3.2. Modeling Constraints

The constraints and simplifications considered in the models developed for the simple expander – nitrogen and the two expander – nitrogen process studied in this paper are:

1. The pressure drop in all heat exchangers and coolers is neglected (He, & Ju, 2014).
2. The isentropic efficiency of compressors and expanders is assumed to be 80% (He, & Ju, 2014).
3. No liquid enters the compressor.
4. Temperature crossing does not occur in heat exchangers (He, & Ju, 2014).
5. The minimum temperature difference between the cold and the hot currents is 3 °C (Venkatarathnam, 2008).
6. Heat losses in heat exchangers are negligible (He, & Ju, 2014).

3.3. The Rmodynamic Modeling

For the thermodynamic modeling of liquefaction processes, the stable Aspen Hysys software model has been used. Thermodynamic modeling of processes is subject to the thermodynamic analysis of each of its components, including compressors, heat exchangers, and expanders, and in the following, the thermodynamic relationships governing each of them will be presented.

3.3.1. Compressors

In the cycles studied in this study, two-stage compressors were used to compress the stream output from the multi-current (operator) converter to the condensing pressure. The compressor power consumption at each compression stage is calculated as portrayed in Eq. (11) to (14) according to its isentropic efficiency:

$$W_1 = \dot{m}_{ref}(h_7 - h_6) = \frac{W_{min,1}}{\eta_{comp}} \qquad (11)$$

$$W_2 = \dot{m}_{ref}(h_9 - h_8) = \frac{W_{min,2}}{\eta_{comp}} \qquad (12)$$

$$W_3 = \dot{m}_{ref}\left(h_{7,2} - h_{6,2}\right) = \frac{W_{min,3}}{\eta_{comp}} \qquad (13)$$

$$W_4 = \dot{m}_{ref}\left(h_{9,2} - h_{8,2}\right) = \frac{W_{min,4}}{\eta_{comp}} \qquad (14)$$

3.3.2. Multi-Current Coolers and Heat Exchangers

In the simple expander – nitrogen process, two coolants, and one multi-current heat exchanger are used and in the two expander – nitrogen process, four coolants, and two multi-current heat exchangers are used for two closed nitrogen cooling cycles. Coolers are responsible for reducing the hot gas temperature of the compressor output. Due to the small amount of heat dissipation, the amount of heat exchange in the coolant can be expressed in Eq.(15) to (18):

$$Q_1 = \dot{m}_{ref}(h_8 - h_7) \qquad (15)$$

$$Q_2 = \dot{m}_{ref}(h_3 - h_9) \qquad (16)$$

$$Q_3 = \dot{m}_{ref}(h_{8-2} - h_{7-2}) \qquad (17)$$

$$Q_4 = \dot{m}_{ref}(h_{3-2} - h_{9-2}) \qquad (18)$$

The responsibility of the multi-current heat exchanger is to transfer heat between the cold and hot streams of the process. In this study, the converter used in all three pre-cooling and liquefaction cycles is a three-flow type. The process currents of each converter include two hot currents and one cold current.

Heat transfer equilibrium in the simple expander – nitrogen process converter and pre-cooling converter of the two expander – nitrogen process is:

$$Q_{5-6} = Q_{1-2} + Q_{3-4} \qquad (19)$$

Heat transfer equilibrium in liquefaction converter of the two expander – nitrogen process is:

$$Q_{5,2-6,2} = Q_{2-13} + Q_{3,2-4,2} \qquad (20)$$

Eq. (19) and (20) can be expanded as follows based on mass flow rates and in the downstream and upstream enthalpy differences

$$Q_{1-2} = \dot{m}_{feed}(h_2 - h_1) \quad (21)$$

$$Q_{3-4} = \dot{m}_{ref}(h_4 - h_3) \quad (22)$$

$$Q_{5-6} = \dot{m}_{ref}(h_6 - h_5) \quad (23)$$

$$Q_{2-13} = \dot{m}_{feed}(h_{13} - h_2) \quad (24)$$

$$Q_{3,2-4,2} = \dot{m}_{ref}(h_{4,2} - h_{3,2}) \quad (25)$$

$$Q_{5,2-6,2} = \dot{m}_{ref}(h_{6,2} - h_{5,2}) \quad (26)$$

3.3.3. Expanders

In expanding processes, gas expansion is carried out in a turbine, or an expander, during a process close to the constant entropy, during which some power is generated. The amount of power output in an expander is shown.

In the simple expander – nitrogen process:

$$W_{Exp} = \dot{m}_{ref}(h_4 - h_5) = W_{max,Exp} \times \eta_{Exp} \quad (27)$$

In the two expander – nitrogen process:

$$W_{Exp,1} = \dot{m}_{ref}(h_4 - h_5) = W_{max,Exp,1} \times \eta_{Exp} \quad (28)$$

$$W_{Exp,2} = \dot{m}_{ref}(h_{4,2} - h_{5,2}) = W_{max,Exp,2} \times \eta_{Exp} \quad (29)$$

3.3.4. Power Consumption of the Processes Studied:

In the simple expander – nitrogen process:

$$W_{net} = W_1 + W_2 \quad (30)$$

$$W_{net} = W_1 + W_2 - W_{Exp} \quad (31)$$

In the two expander – nitrogen process:

$$W_{net} = W_1 + W_2 + W_3 + W_4 \quad (32)$$

$$W_{net} = W_1 + W_2 + W_3 + W_4 - W_{Exp,1} - W_{Exp,2} \quad (33)$$

3.4. Operating Conditions of Liquefaction Cycles

Considering the required liquefaction capacity of Table 1, the specifications of the feed gas inlet to the liquefaction unit in Table 3, as well as the review of previous research on the design of the peak shaving liquefaction cycles (Moradi et al., 2015), the basic operating conditions of the simple expander – nitrogen and the two expander – nitrogen cycles studied in this paper are described in Table 4.

It is necessary to explain that some design parameters such as the coolant temperature after the first and the second cooling cycles, discharge and suction pressures in the two expander – nitrogen process in both pre-cooling and liquefaction cycles are considered equals.

3.5. Heat Exchanger Composite Curves for Each Process to Better Understand the Problem

The composite curve of the heat exchangers is shown in Figures 4 – 6

Table 4. Process design parameters

Process specifications	Simple expander – nitrogen	Two expander – nitrogen
Refrigerant temperature after first cooling	36 ºC	36 ºC
Refrigerant temperature after second cooling	27 ºC	27 ºC
Discharge pressure	100 bar	80 bar
Suction pressure	6.3 bar	10 bar
Feed gas flow rate	20454 kg/h	20454 kg/h
Feed gas Temperature	32 ºC	32 ºC
Feed gas pressure	60 bar	60 bar

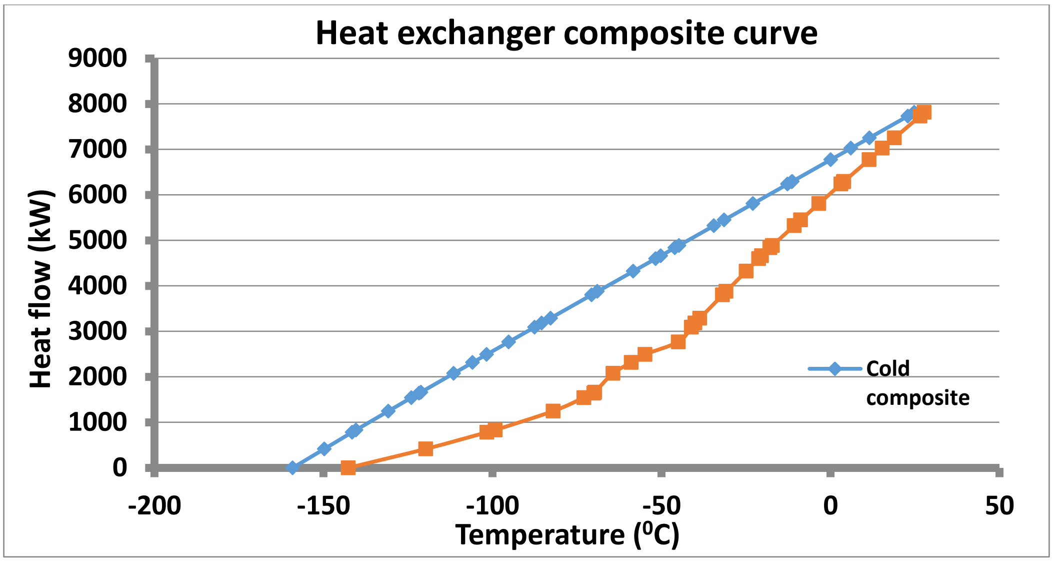

Figure 4. Heat exchanger composite curve for simple expander-nitrogen process

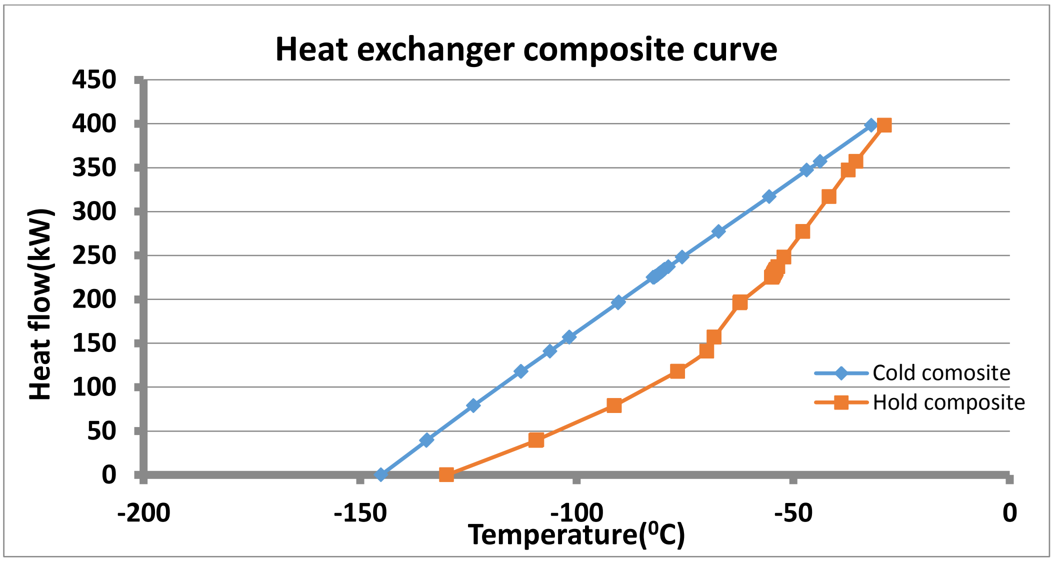

Figure 5. Heat exchanger composite curve for two expander-nitrogen processes (first cycle)

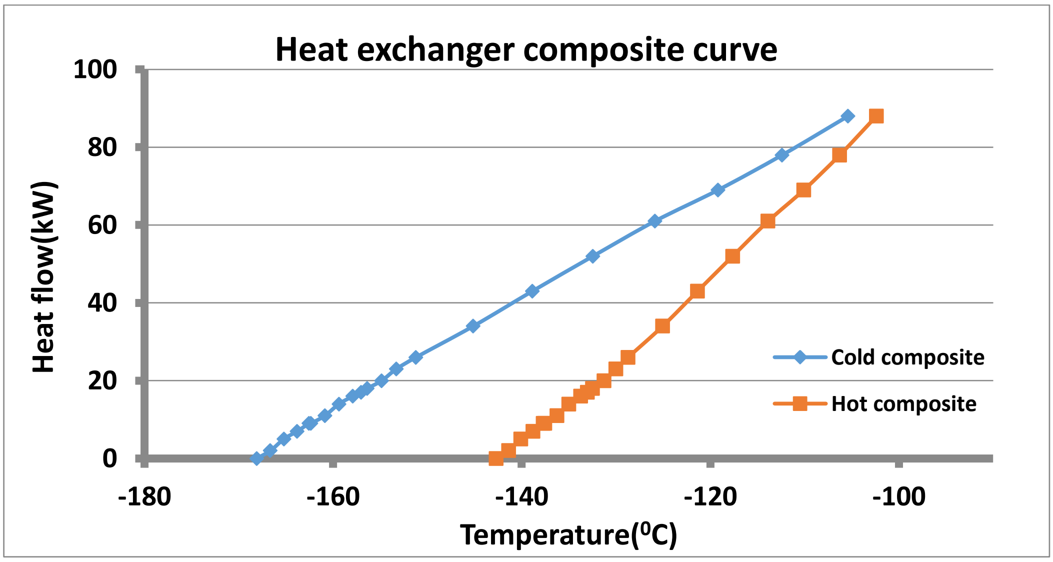

Figure 6. Heat exchanger composite curve for two expander-nitrogen processes (second cycle)

4. Sensitive Analysis

As mentioned in the introduction, the - present study aims to investigate the sensitivity of the simple expander – nitrogen and non-dependent two expander – nitrogen processes to changes in environmental and operating conditions. These changes can be studied by sensitive analysis of the operating conditions (James et al., 1995), (Chen, & Tong, 2004). The purpose of the sensitivity analysis is to compare different parameters affecting the model on the same basis (Qureshi, & Zubair, 2006). Since different parameters of a model are of different definitions, the sensitivity coefficients are generally normalized, so different parameter definitions are available for direct comparison. Here's how to extract normalized sensitivity coefficients for different parameters of a model.

4.1. Sensitive Analysis Theory

In a developed mathematical model for a thermodynamic system, any independent variable input x can be expressed as in Eq. (34):

$$X = \bar{X} \pm U_X \quad (34)$$

In Eq. (34), $\bar{X}$is the nominal value of the variable and U_X is its uncertainty. $\pm U_X$ is a specified interval where the value of the X variable is correct with a usual 95% certainty. It should be noted that any data or variable input to a model is associated with an uncertainty that may be due to the measurement's errors, lack of accurate information (disturbance or fluctuations in the studied variable), or lack of understanding of the behavior of the case study system (Saltelli, 2000). The uncertainties in the input data overshadow the confidence of the response or the output of the model. Suppose the function $Y(X)$ is a univariate function, in which the uncertainty of the Y response caused by the uncertainty of the X variable is:

$$U_Y = \frac{dY}{dX} U_X \quad (35)$$

Now if $Y = Y(X_1, X_2, \dots, X_N)$ is a multivariate function, then the uncertainty in Y, as a result of all the uncertainties of the independent input variables, can be calculated as the square root of the sum of the square uncertainties, which are due to independent input variable on Y (A. Saltelli, 2000):

$$U_Y = \left(\sum_{i=1}^{N} \left(\frac{\partial Y}{\partial X_i} U_{X_i} \right)^2 \right)^{0.5} \quad (36)$$

Each partial derivative in the above equation expresses the sensitivity of the Y parameter to the X_i partial variations. Using the nominal values, the uncertainties of the Y response and the input variables can be changed into a normalized variable and Eq. (36) can be expressed as follows:

$$\frac{U_Y}{\bar{Y}} = \left\{ \sum_{i=1}^{N} \left[\left(\frac{\partial Y}{\bar{Y}} \frac{\bar{X}_i}{\partial X_i} \right) \left(\frac{U_{X_i}}{\bar{X}_i} \right) \right]^2 \right\}^{0.5} \quad (37)$$

The normalized expressions to the right of Eq. (37), are the Normalized Sensitivity Coefficient (NSC) and the Normalized Uncertainty (NU), respectively. Thus, Eq. (37) can be expressed as follows:

$$\frac{U_Y}{\bar{Y}} = \left\{ \sum_{i=1}^{N} NSC_{X_i} NU_{X_i} \right\}^{0.5} \quad (38)$$

The partial derivative value in Eq. (37) can be replaced by its discrete expression. Therefore, the normalized sensitivity and uncertainty coefficients of each input variable can be calculated as follows:

$$NSC_{X_i} = \left(\frac{\Delta Y}{\bar{Y}} \frac{\bar{X}_i}{\Delta X_i} \right)^2 \quad (39)$$

$$NU_{X_i} = \left(\frac{U_{X_i}}{\bar{X}_i} \right)^2 \quad (40)$$

The sensitivity coefficient shows how much change in the output of the model one should expect with the change in a given input variable. Sensitivity analysis can study changes in a system's response to changes in its design variables and parameters. This analysis examines how a model's (numerical or experimental) response affects the changes in the input data as well as other parameters influencing the model. Since in the theory presented in this research the sensitivity coefficients of the input variables have been normalized with the nominal values, it is possible to identify and prioritize the important and influential parameters of the model (Qureshi and Zubair, 2006). It is clear that the uncertainties of all input variables to the model cannot be assumed to be the same, but rather, given the type of the variable, an appropriate uncertainty should be considered. It should be noted, however, that all uncertainties must be expressed with the same degree of confidence (Saltelli et al., 2000).

4.2. The Method Used for Sensitive Analysis

Sensitive analysis can be performed using the perturbation analysis method. The method of this analysis is as follows:

1. Calculated the model output using the nominal values of the independent input variables and call edit Y.
2. Increased the value of the input variable X_i to U_{X_i} and calculated the model response according to this new value $\left(X_{i^+} = \bar{X}_i + U_{X_i}\right)$ assuming the value of the other input variables to be constant and named it Y_{i^+}.
3. Calculated the value of $Y_{i^-}$by reducing the value of the input variable X_i to the perturbation value$\left(X_{i^-} = \bar{X}_i - U_{X_i}\right)$ and keeping the value of the other input variables constant.
4. Calculated the values for $\Delta X_i = |X_{i^+} - X_{i^-}|$ and $\Delta Y_i = |Y_{i^+} - Y_{i^-}|$.
5. Calculated the normalized sensitivity coefficients and normalized uncertainty values of each variable according to Eq. (39) and (40).
6. After calculating the normalized sensitivity coefficients and normalized uncertainty values of each variable, the response uncertainty was obtained from Eq. (38) according to the considered perturbations for all variables.

Sensitivity analysis was performed by a link from the Hysys software to the Matlab programming language.

4.3. Sensitive Analysis Expansion on the Studied Liquefaction Processes

In this section, we expand the sensitivity analysis to the simple expander – nitrogen and two expander – nitrogen liquefaction processes described in the previous sections. The first step in the sensitivity analysis is to determine the uncertainty of the number of perturbations expected in different model parameters. Table 5 shows the perturbation values considered for various parameters of the liquefaction processes in the present study. These values have been determined in accordance with the Iranian Gas Standards (IGS-C-IN-105, 2015) as well as previous research conducted in this field (Amidpour et al., 2015), (Mafi, 2009).

Power consumption in liquefaction cycles (model output) is a function of various variables including compressor suction and discharge pressures, pre-expansion temperature, post-coolant temperature, coolant flow and feed gas conditions (pressure, temperature, flow rate, and the component composition percentage).

Table 5. Perturbations are intended for different input independent variables

Study variable	Component composition percentage	Flow rate (kg/h)	Pressur (kPA)	Temperature (^{0}C)
The amount of disturbance	0.5%	200	20	1

5. Analysis Results

The power consumption parameter of the simulated model in Aspen Hysys software for both studied cycles is shown in Table 6:

5.1. Investigating the Sensitivity of the Operational Pressures

According to the values presented in Tables 7 and 8 and Fig. 7, it is clear that both processes are more sensitive to cooling pressure changes (suction pressure and discharge). In terms of feed gas pressure variations (which we find more in peak shaving units), the sensitivity of the two expander – nitrogen processes is less.

5.2. Investigating the Sensitivity of the Operating Temperatures

The information gained from evaluating the sensitivity of the two processes to the operating temperatures caused by perturbation is presented in Tables 9 and 10 and Fig.8. The results indicate that in the case of operating temperatures, except in one case, each process exhibits a different reaction to the changes. In terms of the feed gas temperature variations, the sensitivity of the two expander – nitrogen process is less.

Table 6. Power consumption parameter of the simulated model in Hayes software

Process specifications	Two expander – nitrogen	Simple expander – nitrogen
Process power consumption	7.73 MW	12.45 MW
The ratio of consumption power of liquefaction unit to power plant	2.32%	3.75%

Table 7. Information gained in evaluating the sensitivity of the two processes to the operating Refrigerant pressure

Study variable	Two expander – nitrogen process (liquefaction the cycle)		Two expander – nitrogen process (Pre-cool the cycle)		Simple expander – nitrogen process	
	NU	NSC	NU	NSC	NU	NSC
Suction pressure	4.0×10^{-4}	1.8×10^{-2}	4×10^{-4}	2.3×10^{-1}	1.0×10^{-3}	4.7×10^{-1}
Discharge pressure	6.3×10^{-6}	8.1×10^{-2}	6.3×10^{-6}	4.2×10^{-1}	4.0×10^{-6}	3.6×10^{-1}

Table 8. Information gained in evaluating the sensitivity of the two processes to the operating feed gas pressure

Study variable	two expander – nitrogen process		simple expander – nitrogen process	
	NU	NSC	NU	NSC
Feed gas pressure	1.1×10^{-5}	1.5×10^{-3}	1.1×10^{-5}	1.5×10^{-2}

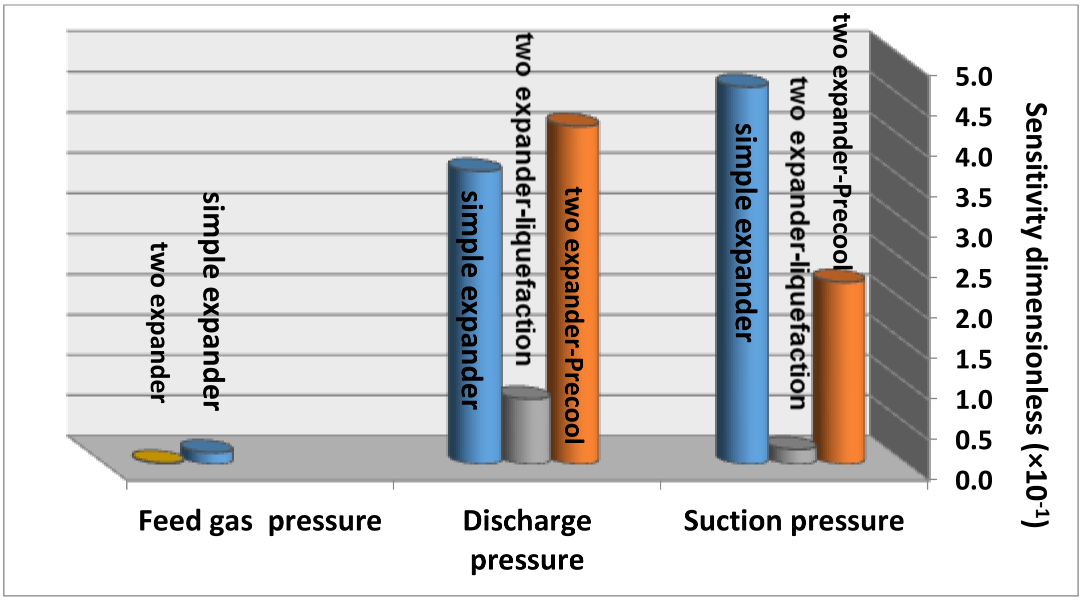

Figure 7. Comparison of the sensitivity of liquefaction processes to pressure variables

Table 9. Information gained in evaluating the sensitivity of the two processes to the operating Refrigerant Temperature

Study variable	Two expander – nitrogen process (liquefaction the cycle)		Two expander – nitrogen process (Pre-cool the cycle)		Simple expander – nitrogen process	
	NU	NSC	NU	NSC	NU	NSC
Temperature before the expander	1.2×10^{-4}	1.9×10^{-2}	3.3×10^{-4}	3.7×10^{-3}	4.9×10^{-4}	8.2×10^{-3}
Temperature after the first cooler	7.7×10^{-4}	5.4×10^{-4}	7.7×10^{-4}	4.3×10^{-3}	7.7×10^{-4}	1.0×10^{-2}
Temperature after the Second cooler	5.0×10^{-4}	2.1×10^{-3}	3.4×10^{-4}	2.1×10^{-2}	1.4×10^{-3}	9.2×10^{-3}

Table 10. The information gained in evaluating the sensitivity of the two processes to the operating feed gas Temperature

Study variable	Two expander – nitrogen process		Simple expander – nitrogen process	
	NU	NSC	NU	NSC
Feed gas Temperature	9.8×10^{-4}	1.7×10^{-5}	9.8×10^{-4}	1.7×10^{-4}

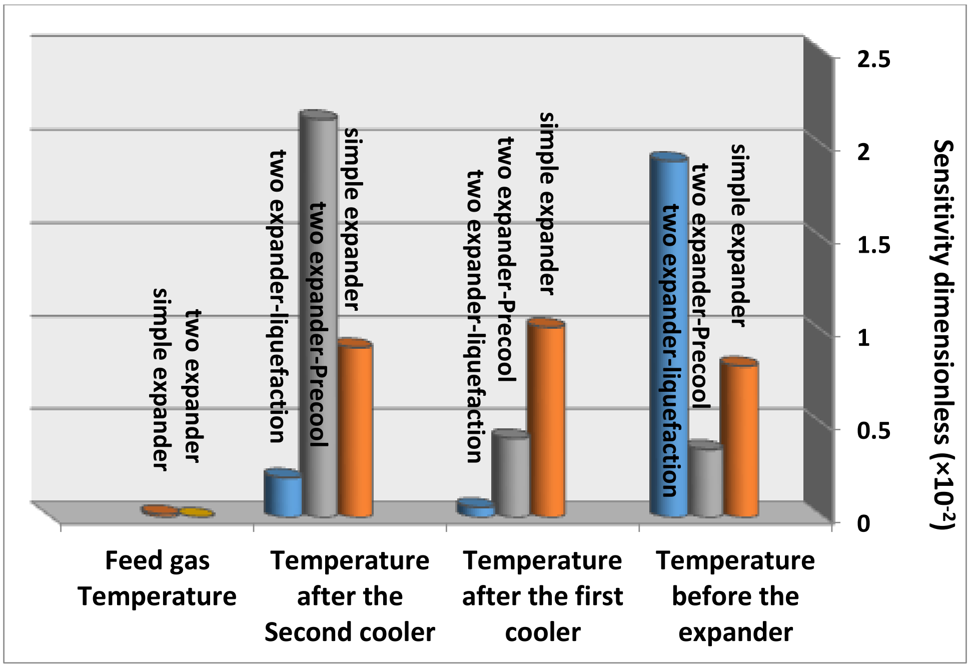

Figure 8. Comparison of the sensitivity of liquefaction processes to Temperature variables

5.3. Investigating the Sensitivity of the Feed Gas Composition Percentage

The data presented in Table 11 and Fig. 9shows the sensitivity of the processes studied to the changes in the feed gas composition. Changes in any components of the feed gas are of the most important factors in the peak shaving units. Any increase or decrease in the components of the feed gas modifies some of its properties, such as its thermal values, and affects its efficiency, the amount of fluid produced, and the power consumption of the unit. The expander – nitrogen process is more sensitive to changes in the component composition percentage (in all components, especially methane and nitrogen).

5.4. Investigating the Sensitivity of the Two Cycles to the Flow Discharge

The feed gas flow and the coolant discharge are effective parameters in changing power consumption and the normalized values of sensitivity and uncertainty coefficients related to the coolant discharge and the feed gas flow of both expander – nitrogen and two expander – nitrogen processes are shown in Tables 12 and 13 and Fig. 10, respectively. Changes in the feed gas flow have less impact on the power consumption of the two expander – nitrogen process, which indicates greater sustainability of the process due to reduced capacity.

Table 11. Information gained in evaluating the sensitivity of the two processes to the feed gas composition percentage

Study variable	Two expander – nitrogen process		Simple expander – nitrogen process	
	NU	NSC	NU	NSC
Nitrogen	1.6×10^{-2}	9.6×10^{-6}	1.6×10^{-2}	7.5×10^{-3}
Methane	3.3×10^{-5}	1.1×10^{-3}	3.3×10^{-5}	4.4×10^{-2}
Ethane	8.3×10^{-3}	3.2×10^{-4}	8.3×10^{-3}	4.9×10^{-4}
Propane	6.3×10^{-2}	1.7×10^{-5}	6.3×10^{-2}	2.3×10^{-5}
n-Butane	1.0	6.7×10^{-8}	1.0	1.6×10^{-7}
i-Butane	1.0	1.5×10^{-7}	1.0	1.6×10^{-7}
i-Pentane	1.0	2.1×10^{-7}	1.0	1.5×10^{-6}

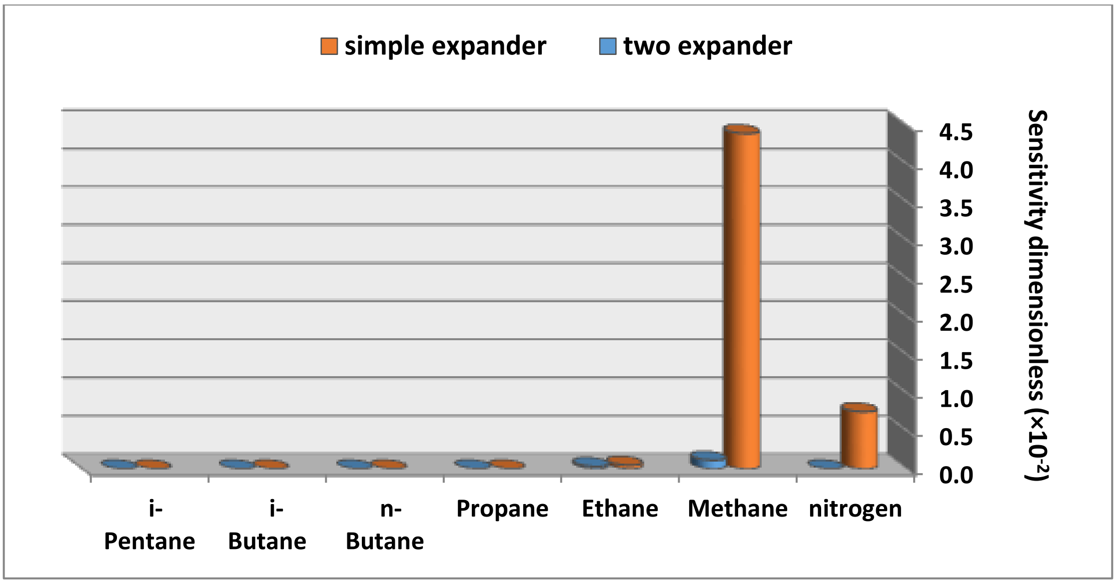

Figure 9. Comparison of the sensitivity of liquefaction processes to feed gas composition variables

Table 12. Information gained in evaluating the sensitivity of the two processes to the feed gas flow

Study variable	Two expander – nitrogen process		Simple expander – nitrogen process	
	NU	NSC	NU	NSC
Feed gas flow	9.6×10^{-5}	3.7×10^{-2}	9.6×10^{-5}	3.8×10^{-1}

Table 13. Information gained in evaluating the sensitivity of the two processes to the Refrigerant flow

Study variable	Two expander – nitrogen process (liquefaction the cycle)		Two expander – nitrogen process (Pre-cool the cycle)		Simple expander – nitrogen process	
	NU	NSC	NU	NSC	NU	NSC
Refrigerant flow	2.2×10^{-5}	1.2×10^{-1}	3.0×10^{-6}	8.8×10^{-1}	1.9×10^{-6}	3

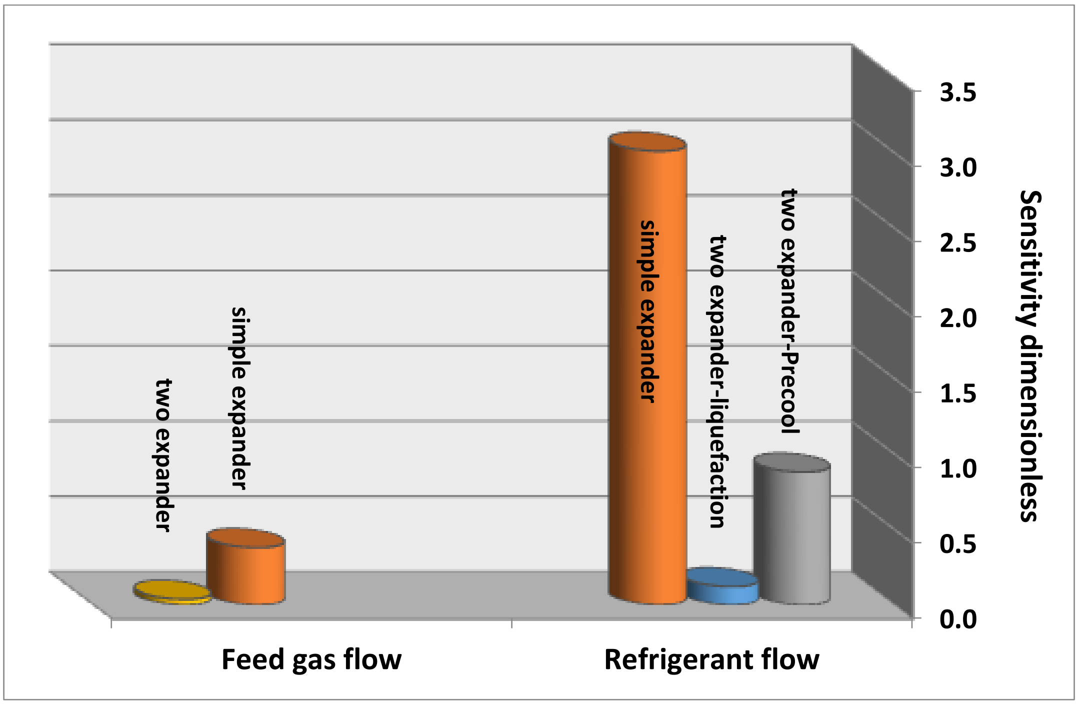

Figure 10. Comparison of the sensitivity of liquefaction processes to flow discharge variables

5.5. Uncertainty in Power Consumption of Expander – Nitrogen Processes and Multivariate Coolants

Table 14 displays the calculated uncertainties in power consumption of expander – nitrogen and non-dependent two expander – nitrogen processes by applying Eq. (38) and using the data in Tables 7-13 and the uncertainty in power consumption of both liquefaction processes for the parameters discussed in the previous sections. It should be noted that the greater the uncertainty in a model's response to perturbations, the higher the accuracy of the equipment needed to measure the input variables to the model (Amidpour et al., 2015), (Mafi, 2009). The reason behind the increasing accuracy of the equipment measurement requirements with increasing uncertainty in the model response presented for a system is that these systems require more precise control loops (Amidpour et al., 2015). One advantage of the normalized sensitive analysis is that it can compare parameters of different definitions (parameters like temperature and pressure). Frequency diagrams of power consumption uncertainties of both expander – nitrogen and the two expander – nitrogen processes are shown in Figures 11and 12with respect to all environmental and operational variables, where uncertainties for the family of quantities (for example compressive quantities including suction pressure, discharge, feed, etc.) are calculated. The power consumption in these processes is another expression for the thermodynamic efficiency parameter of the cycles, which is referred to here as the model response. As shown in Figures 11 and 12, in the expander – nitrogen process, based on priority, pressure control and control over the feed gas components composition percentage are more important. Based on priority, pressure control and temperature control are more important than other parameters in the two expander – nitrogen process. Also, the uncertainties in power consumption concerning all values (16 parameters for the expander – nitrogen process and 16 parameters for the two expander – nitrogen process) can also be calculated using Eq. (38) in which the values are calculated 2.58% and 1.14% for the expander – nitrogen and the two expander – nitrogen processes, respectively. These values emphasize the lower sensitivity of the two expander – nitrogen processes compared to all environmental and operational variables.

Table 14. Uncertainty in power consumption of expander – nitrogen processes and multivariate coolants

Parameters	Two expander – nitrogen process (liquefaction the cycle)	Two expander – nitrogen process (Pre-cool the cycle)	Simple expander – nitrogen process
Suction pressure	0.27%	0.95%	2.17%
Discharge pressure	0.07%	0.16%	0.12%
Feed gas pressure	0.01%	0.01%	0.04%
Temperature before the expander	0.15%	0.11%	0.2%
Temperature after the first cooler	0.06%	0.18%	0.28%
Temperature after the second cooler	0.1%	0.27%	0.36%
Feed gas temperature	0.01%	0.01%	0.04%
Percentage of feed gas composition	0.21%	0.21%	1.12%
Feed gas flow rate	0.19%	0.19%	0.6%
Refrigerant flow rate	0.16%	0.16%	0.24%

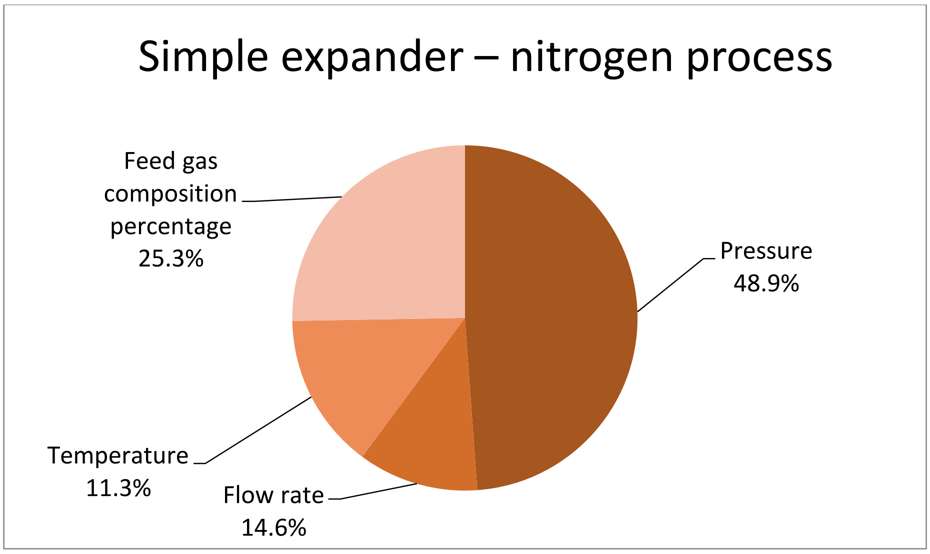

Figure 11. Response of simple expander-nitrogen process model to input perturbations

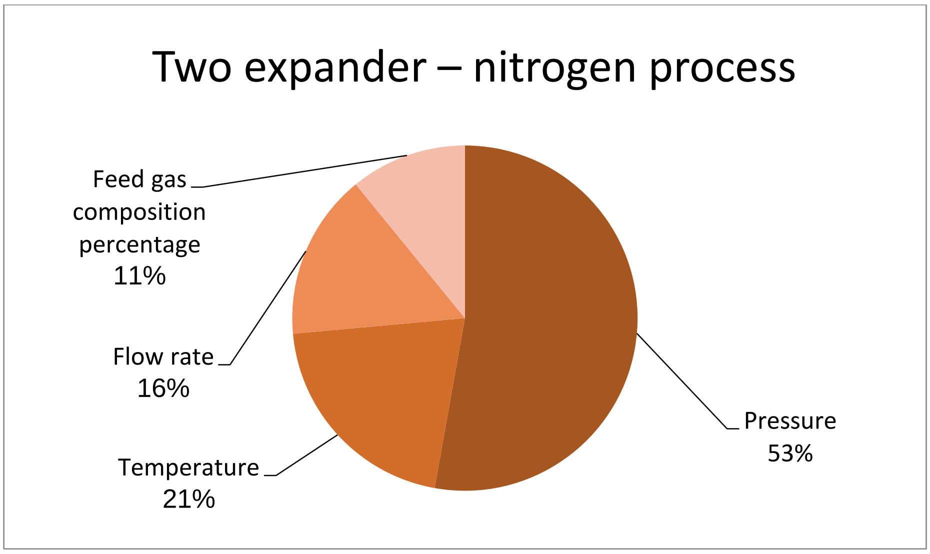

Figure 12. Response of two expander-nitrogen process model to input perturbations

Table 15. Heat exchanger stream data of simple expander – nitrogen processes

Stream data					MC_p (kW/ °C)	ΔH (kW)
7	298.5 °C	Cooler	36 °C	Ref	44.3	9813.6
9	133.9 °C	Cooler	26.5 °C	Ref	45.5	5006.2
3	26.5 °C	LNG	-45 °C	Ref	48.3	3656
5	-159.1 °C	LNG	24.8 °C	Ref	45.3	7846.7
1	32 °C	LNG	-142.6 °C	Feed	14.4	4155

Table 16. Heat exchanger stream data of two expander – nitrogen processes

Stream data					MC_p (kW/ ^{0}C)	ΔH (kW)
7	79.6 ^{0}C	Cooler	36 ^{0}C	Ref	35	1533
9	159.7 ^{0}C	Cooler	-53.9 ^{0}C	Ref	36.1	8133.3
3	-53.9 ^{0}C	LNG	-55 ^{0}C	Ref	43.9	49.1
5	-145.2 ^{0}C	LNG	-31.9	Ref	37.8	3975.4
7-2	-26.1 ^{0}C	Cooler	36 ^{0}C	Ref	13.3	819.7
9-2	159.7 ^{0}C	Cooler	-48.7 ^{0}C	Ref	13.4	2928.6
3-2	-48.7 ^{0}C	LNG	-86 ^{0}C	Ref	16	650.4
5-2	-168.1 ^{0}C	LNG	-105.4 ^{0}C	Ref	16.3	876.2
1	32 ^{0}C	LNG	-130 ^{0}C	Feed	14.4	3929
2	-130 ^{0}C	LNG	-142.7 ^{0}C	Feed	18.1	224.6

6. Discussion and Conclusion

This study aims to propose an appropriate cycle for liquefaction and storing natural gas in the vicinity of the country's power plants due to frequent changes in environmental and operating conditions. To this end, considering the capacity required for liquefaction units for storage over a 200-day interval for a common 332 MW power generation plant in Iran, both simple expander – nitrogen and non-dependent two expander – nitrogen processes were selected and their behaviors to environmental and operational changes were studied based on the normalized sensitive analysis. It should be noted that we had tried to use actual information for the input information needed to simulate the processes (such as pressure, temperature and feed line composition, feed gas inlet flow to the compressor's efficiency liquefaction units and expanders), and in case of the lack of information, we referred to the reputable worldwide references. After modeling the two processes (before performing sensitive analysis), their power consumption was compared and the results showed that the power consumption of a liquid generator unit that uses the non-dependent two expander-nitrogen process is approximately 62% of the power consumption of a similar unit utilizing a simple expander-nitrogen process. This indicates the superiority of the two expander – nitrogen process over the simple expander – nitrogen process in power consumption and other thermodynamic parameters such as specific work and heat efficiency. The results of this section also showed the importance of the ratio of the power consumption of the simple expander and the two expander liquefaction processes, which showed the total power generation capacity of the power plant is 3.75% and 2.32% for both processes respectively. One of the most important parameters in choosing the proper process for liquefying the natural gas, however, is the sensitivity of the liquefaction processes to changes in environmental and operating conditions. In this research, the perturbation analysis method was used to identify the behavior of liquid forming processes and to provide quantitative indices to compare their sensitivity on an equal basis. The results of the analysis show that the simple expander – nitrogen process is more sensitive to most of the studied variables compared to the non-dependent two expander – nitrogen process. This indicates that these processes require more precise and efficient control loops to maintain cycle stability around the design point, thereby increasing the initial investment cost of the liquefaction process.

Given the frequent changes in environmental and operating conditions in Iran's gas distribution lines, priority is given to providing cycles with a lower sensitivity advantage than cycles with a lower power consumption advantage. Research into the development and delivery of cycles with a simpler layout and lower sensitivity to environmental and operational variables that also have the advantage of lower power consumption than the non-dependent two expander – nitrogen cycle can serve as new horizons for the present study.

The novelty of this paper is that the sensitivity of the two processes in environmental and operational conditions is investigated and a less sensitive cycle is selected. Therefore, it is suggested that sensitivity analysis of environmental and operational conditions should be considered as an important priority in selecting the appropriate cycle for natural gas liquefaction processes.

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