Energy and Exergy Optimization of a mini-scale Nitrogen Dual Expander Process for Liquefaction of Natural Gas

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Abstract

Nitrogen expansion processes are suitable for mini or small-scale liquefied natural gas plants, due to their simplicity and less equipment. However, they consume a high amount of energy and any attempt to reduce the energy consumption and improve the quality of energy (work potential of energy), leads to enhance the process efficiency and profitability. A mini-scale nitrogen dual expander natural gas liquefaction process is simulated and analyzed by Aspen HYSYS simulator. Then, in order to optimize energy performance of the process, some influencing variables are adjusted using the genetic algorithm approach provided by MATLAB software in two separate optimization cases with different objective functions. Specific energy consumption and total exergy destruction are considered as the objective functions of the optimization cases (namely energy and exergy cases), which represent quantity and quality of energy, respectively. The most important operating variables of the process, refrigerant molar flow, refrigerant temperatures and refrigerant pressures, are selected via a sensitivity analysis. The results indicate that in both of the optimization cases, the specific power consumption of the process is reduced 7.1%. However, the total exergy destruction for exergy case decreases 9.55% which is slightly a more desirable result than the energy case. Also, total exergy efficiency of the process in exergy case is 4.4% higher than the other case which reveals that considering the quality aspect of energy as the objective can improve the performance of the process more appropriately.

Keywords: Liquefied natural gas, Nitrogen expansion, Optimization, Energy, Exergy destruction, Efficiency.

Nomenclature

$\dot{E}$	exergy rate (kW)	*F*	fuel
$\dot{m}$	mass flow (kg/hr)	*min*	minimum
h	molar enthalpy (kJ/kgmole)		
s	molar entropy (kJ/kgmole°C)	*Superscripts*	
T	temperature (°C)	*tot*	total
$\dot{W}$	compressor duty (kW)		
P	pressure (bar)	*Abbreviations*	
x	decision variable	*NG*	natural gas
		LNG	liquefied natural gas
Greek letters		*SPC*	specific power consumption
η	adiabatic efficiency (%)	*C*	compressor
ε	exergy efficiency (%)	*EXP*	expander
Δ	gradient	*E*	heat exchanger
		AC	air cooler
Subscripts		*V*	two phase separator
in	inlet	*VLV*	expansion valve
i	component	*PRSV*	Peng-Robinson-Stryjek-Vera
in	inlet	*COP*	coefficient of performance
out	outlet	*SMR*	single mixed refrigerant
COMP	compressor	*DMR*	dual mixed refrigerant
EXP	expander	C_3MR	propane precooled mixed refrigerant
k	kth component	*MFC*	mixed fluid cascade
D	destruction	*GA*	genetic algorithm
P	product		

1. Introduction

Today, there is an urgent need to obtain a sustainable and equal accessibility to abundant and inexpensive natural gas (NG) energy source and decrease negative environmental effects of traditional fossil fuels. Therefore, feasible and economical ways for transportation of NG have to be considered and developed. Among different ways, NG liquefaction to produce liquefied natural gas (LNG) is the most economical, especially for long-distance transport and high-density storage [1]. An LNG production process consists of one or more refrigeration cycles which consume a high amount of energy to liquefy NG through reducing its temperature to methane boiling point. This leads to the significant reduction in NG volume and decreasing the size and cost of NG storage and transportation [2]. Like the other refrigeration cycles, the main contribution to the energy consumption of LNG processes belongs to compressors power which is mainly dependent on the temperature differences in heat exchangers [3]. Therefore, any effort to decrease energy consumption of the compressors in liquefaction plants will lead to a more feasible and profitable process. A common objective in the most recent optimization studies is to minimize total power consumption of the liquefaction process [3] and also maximize LNG production [4] which is directly related to the quantity of energy consumption. However, the second-law aspect or quality of energy in LNG processes have not been considered dramatically as an objective for optimization works. Minimizing specific power consumption (total consumed power for the production of 1 kg LNG) will be useful when the quality of energy is improved through minimizing total exergy destruction produced by process equipment and improving total exergy efficiency of the liquefaction process.

Natural gas liquefaction processes can be divided into two main categories, vapor-compression and expansion, based on the common classification of refrigeration cycles [5]. The main vapor-compression LNG processes are mixed refrigerant systems which include well-known single cycle (SMR), dual cycle (DMR), propane precooled (C_3MR) and mixed fluid cascade (MFC) processes [4,6]. These mixed refrigerant processes introduced and designed by the famous companies such as Linde AG, APCI, etc [7]. The mixed refrigerant is liquefied and vaporized in different parts of these processes and can supply required refrigeration with less energy consumption than pure refrigerant. However, these processes are more complex and have a large number of equipment in their configuration. In the majority of expansion processes, nitrogen is used as a refrigerant and remains in the gas phase in the whole cycle. Due to simplicity which is the main advantage of the nitrogen expansion systems, they are suited for small-scale and mini-scale LNG liquefaction processes [8].

Many studies on energy optimization of the vapor-compression processes have been already reported in the literature including classical cascade [9], SMR [10-17], C_3MR [18-22], AP-X [23], MFC [24] and a novel small-scale liquefaction process with no energy consumption [25]. However, only a few works can be found for the optimization of nitrogen expansion processes. One of the obvious differences between optimization procedure of the two mentioned LNG processes is to consider the composition of refrigerant as an important decision variable in the mixed refrigerant processes. He and Ju [8] presented a novel design of parallel nitrogen expansion liquefaction process for a small-scale LNG plant in skid-mount packages and then, an optimization model with the genetic algorithm method is developed to optimize the process. They finally concluded that the proposed process could be used in small-scale LNG plants with a high exergy efficiency and considerable economic benefits. Yuan et al. [26] designed and optimized a small-scale natural gas liquefaction process based on a single nitrogen expansion with carbon dioxide precooling. They also employed exergy analysis for the main process equipment indicating that compressors contribute the largest proportion of total exergy destruction. Results showed that unit energy consumption of the process was minimized to 9.90 kWh/kmol through optimization. Khan et al. [27] analyzed single and dual nitrogen expander processes to improve their efficiency considering the compression energy minimization as objective using an algorithm inspired by the knowledge of process design variables. Optimization results displayed the specific energy requirement of 0.7449 kWh/kg LNG for single and 0.5007 kWh/kg LNG for dual nitrogen expander processes. He and Ju [28] also introduced an optimal synthesis of expansion liquefaction cycle for a distributed-scale LNG plant using the figure of merit (FOM) to evaluate and select the optimum configuration of liquefaction process. Results revealed that the optimized liquefaction process has two precooling and parallel nitrogen expansion cycles. Song et al. [29] modeled and optimized a single nitrogen expansion process with carbon dioxide precooling utilizing the genetic algorithm optimization tool. The unit energy consumption (kWh/kmol) and the liquefaction rate were considered as the objective functions. Results indicated that the optimized process shows a low unit energy consumption and a high heat transfer efficiency.

A review of the optimization studies which have been carried out on the nitrogen expansion LNG processes reveals that the second-law or quality indicators of refrigeration cycles, such as total exergy destruction and total exergy efficiency, have not been taken as objective functions in the optimization of the processes, yet. In the present study, energy and exergy optimization are applied to a famous mini-scale nitrogen dual expander process for NG liquefaction employing the genetic algorithm approach. Two different cases are carried out considering specific power consumption (SPC) and total exergy destruction ($\dot{E}_D^{tot}$) as the objective functions and the results are evaluated. Influencing decision variables are selected through a sensitivity analysis which is done in the baseline process. Also, optimization constraints are defined regarding design and operating considerations associated with LNG processes. The main idea of this work is to achieve the optimum value of the operating variables which minimize specific energy consumption and total exergy destruction and improve total exergy efficiency. It is hypothesized that considering the total exergy destruction of the process (the quality of energy) as the objective function will also minimize the specific power consumption. Therefore, another aim of the present study is to compare the results of the optimization cases and determine the best parameter as the objective function.

2. Process description

An expansion refrigeration cycle operates using a refrigerant which does not liquefy in any section of the cycle, and the cooling duty is provided by capturing a part of sensible heat [5]. To this, the refrigerant should be compressed to a high pressure and then expanded after temperature reduction by a cooler. Because the refrigerant remains in gas phase within the entire cycle, a certain part of its exergy is recoverable by a turbo-expander. Nevertheless, expansion cycles, especially in natural gas liquefaction, consume larger power compared to vapor-compression cycles such as mixed refrigerant processes. Nitrogen is an appropriate substance as the refrigerant for liquefying natural gas, due to its suitable physical properties and lower boiling point than methane. In general, nitrogen expansion LNG processes are simple compared to the mixed refrigerant processes. Today, numerous processes have been introduced by different companies, and only a few are commercialized.

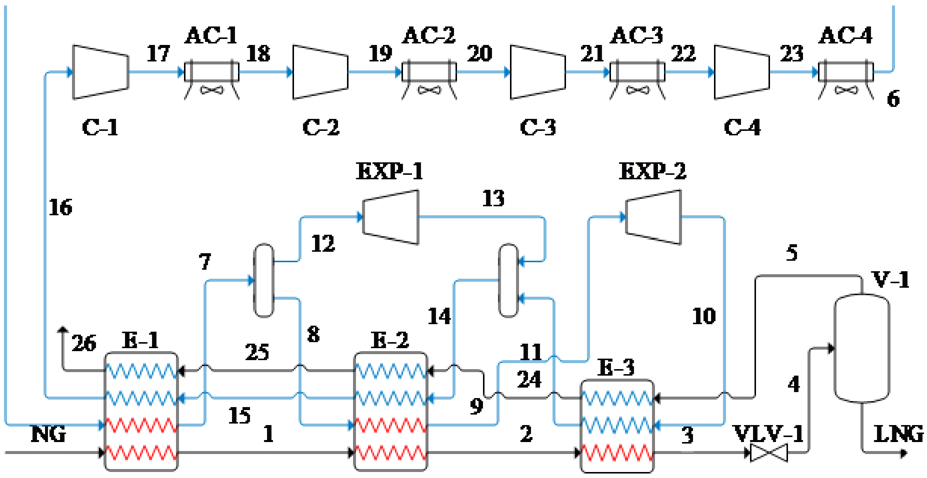


Fig 1. Process flow diagram of the nitrogen expansion process - BHP Billiton.

BHP Billiton is a famous nitrogen dual expansion LNG process designed by BHP Petroleum PTY company which has a simple structure and uses two expanders [30]. Fig. 1 shows the process flow diagram of the process. As illustrated, natural gas enters multi-stream heat exchanger E-1 at 35 °C and is cooled down to -6 °C. Then, it is liquefied and subcooled to -143 °C by passing through E-2 and E-3 heat exchangers, respectively. Finally, its pressure is reduced to 2.53 bar in VLV-1 valve, and the outlet liquid from V-1 separator leaves the process as LNG product with conventional specifications. The refrigerant exits from E-1 at 36.29 °C and 4.5 bar (stream 16) and passes through C-1, C-2, C-3 and C-4 compressors and AC-4 aftercooler. Then, it enters E-1 at 40 °C and 39.5 bar and the outlet stream is divided into two separate parts. The first part (stream 12) expands to 5.5 bar within EXP-1 prior to crossing the mixer and its temperature is reduced to -108.2 °C. The second part (stream 8) enters E-2 and its temperature decreases to -89 °C. It expands to 6 bar and is cooled to -161.7 °C, thus, it provides the required refrigeration of E-3 and is followed by a mixer at -93 °C. The outlet stream of the mixer (stream 14) passes through E-2 at -103.11 °C and it eventually warms up to C-1 suction state by crossing E-1. As the figure shows, the vapor stream from V-1 is returned to the heat exchangers for utilizing its cold duty. This can improve the energy efficiency of the refrigeration cycle. Specifications of the feed gas and LNG product and thermodynamic data of the process streams are presented in Tables 1 and 2, respectively.

Table 1. Specifications of the feed gas and LNG product streams of the process.

	Feed gas	LNG Stream
Mass Flow (tonne/day)	11.08	10.00
Temperature (ºC)	35	-152.34
Pressure (bar)	60	2.53
Components (mole %)		
Methane	92.94	94.47
Ethane	3.00	3.29
Propane	0.48	0.53
i-Butane	0.06	0.07
n-Butane	0.08	0.09
Nitrogen	3.44	1.55

Table 2. Thermodynamic data of the process streams.

Stream No.	Temperature (ºC)	Pressure (bar)	Mass flow (tonne/day)	Exergy (kW)
NG	35	60	11.08	73.7
1	-6	59.5	11.08	74.11
2	-89	59	11.08	96.71
3	-143	58.5	11.08	120.9
4	-152.34	2.53	11.08	116.78
5	-152.34	2.53	1.08	3.55
LNG	-152.34	2.53	10.00	112.64
6	40	39.5	92.91	347.63
7	-6	39	92.91	348.09
8	-6	39	31.20	116.87
9	-89	38.5	31.20	128.63
10	-161.7	6	31.20	98.17
11	-93	5.5	31.20	66.17
12	-6	39	61.72	231.22
13	-108.2	5.5	61.72	139.26
14	-103.11	5.5	92.91	205.13
15	-23.22	5	92.91	156.66
16	36.29	4.5	92.91	141.97
17	69.24	6	92.91	172.44
18	40	5.5	92.91	161.2
19	124.78	11	92.91	242.24
20	40	10.5	92.91	222.54
21	118.37	20	92.91	297.14
22	40	19.5	92.91	281.11
23	128.38	40	92.91	365.67
24	-140	2.03	1.08	2.8
25	-50	1.53	1.08	0.94
26	25	1.03	1.08	0.03

3. Process optimization

3.1. Optimization framework and genetic algorithm

There are two general ways for optimization of energy consumption of liquefaction cycles in LNG plants. One is to change the structure of existing processes and to create a new design and configuration for the cycles based on conceptual method. This is a fundamental way and needs high technological and professional experiences. The other way is to adjust operating variables with the aim of efficiency improvement of liquefaction cycle. In the latter method, liquefaction process must be modeled mathematically before implementing the optimization procedure. In order to avoid complexity and improve accuracy and precision of the model, the process can be simulated using well-known commercial simulators such as Aspen HYSYS. One of the advantages of this simulator is to provide a link with MATLAB software which enables it to utilize its powerful optimization tools in process simulation. Genetic algorithm (GA) is an optimization technique which has an ability to reach a global optimum, especially in an LNG production process which is a non-linear and complex problem with many effective variables and local optimum points [18]. GA is a heuristic optimization algorithm which inspired by natural evolution through modifying a population of individual solutions [31].

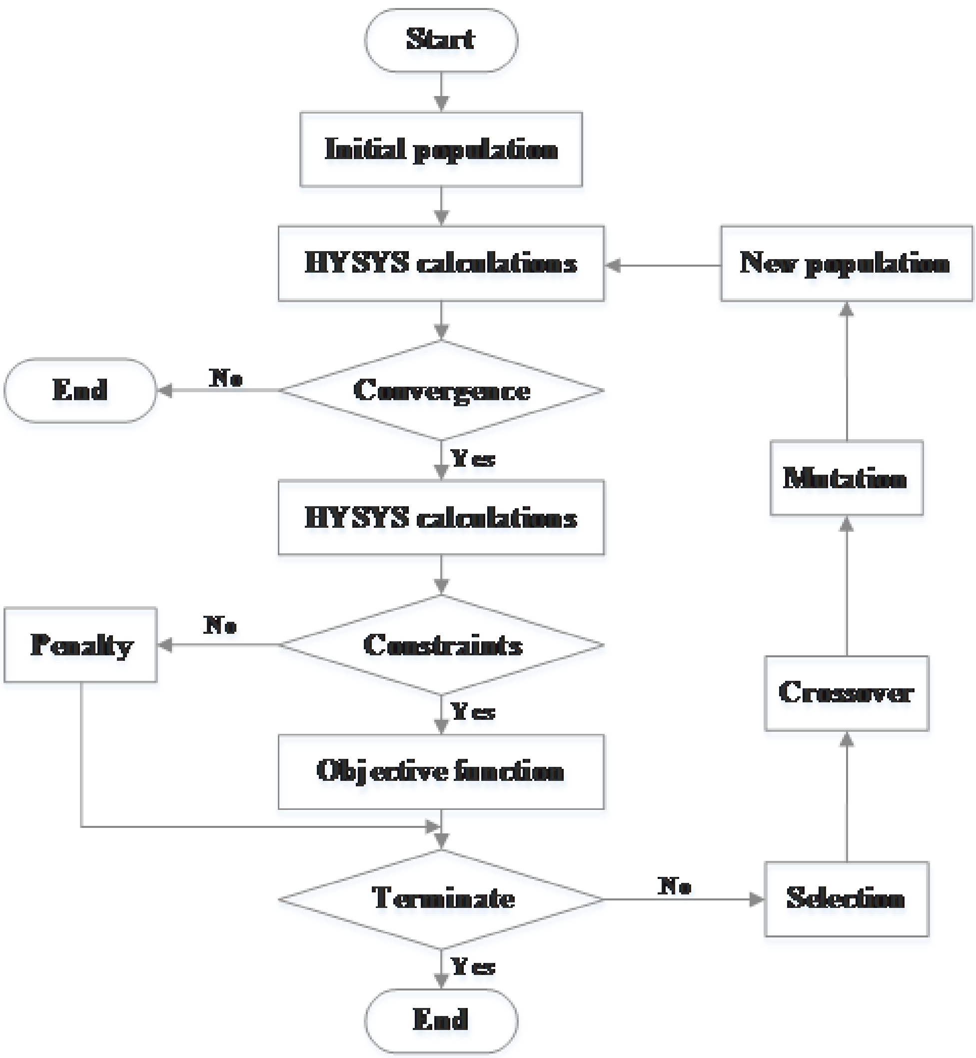


Fig 2. Framework of the optimization procedure with GA.

Since the aim of the present study is to improve the efficiency of a nitrogen dual expansion process through adjusting the main operating variables, the process was simulated by ASPEN HYSYS software and GA approach was used for optimization. Fig. 2 shows the framework of the optimization procedure with GA. As can be seen, a set of random initial population is firstly generated for decision variables. Then, the program calls Aspen HYSYS to run the simulation using the generated variables. The converged simulation is then checked due to the constraints and finally the program calculates the objective function. The algorithm continues by a new generated population while the penalty function is satisfied. Generating each population is carried out based on the genetic concepts utilized in the algorithm via the selection, crossover and mutation parameters. In order to achieve the best result, these GA parameters should be set accurately. Thus, for this study, the value of the parameters summarized in Table 3, were set based on previous successful studies presented in the literature [8,18]. Further explanations about the procedure and GA approach and the parameters can be found elsewhere [8,29,31].

Table 3. The tuning parameters of the genetic algorithm.

Tuning parameters	Value
Population size	200
Maximum number of generations	50 × number of design variables
Reproduction count	0.05 × Population size
Selection method	Tournament
Tournament size	4
Fitness scaling method	Rank
Crossover function	Scattered
Crossover fraction	0.8
Number of crossover points	1
Mutation method	Constraint dependent

3.2. Objective functions

Most studies about LNG plants optimization have been done by considering total or operating costs as the objective function [3,19,28,29]. For an existing liquefaction process with a constant capital cost, it is noteworthy that the main fraction of operating cost is related to compression power. Due to the high energy consumption of natural gas liquefaction processes, many researches have been carried out to improve the efficiency and reduce the required energy in LNG plants. Therefore, specific power consumption which is defined previously as total compressors power to LNG mass flow rate is usually considered as an objective function for optimization purpose [31]. However, decreasing the quantity of energy consumption in a process is more useful when its quality is simultaneously improved. So, to enhance the impact of minimizing the energy consumption, total entropy generation or exergy destruction of the process ($\dot{E}_D^{tot}$) should be reduced. Vatani et al. [32] have proved that SPC and $\dot{E}_D^{tot}$ show a similar trend, and one will reduce with decreasing the other. Therefore, the quality of energy consumption will be improved while its quantity decreases. As mentioned before, one of the aims of the present work is to identify the most appropriate parameter as an objective function for optimization of LNG plants. Thus, the optimization was performed separately for the two different objective functions of SPC and $\dot{E}_D^{tot}$ and the results were eventually compared. The mentioned objective functions can be defined as:

$$\min \quad f_1(X) = \frac{\dot{W}_{tot}}{\dot{m}_{LNG}} \tag{1}$$

$$\min \quad f_2\,(X) = total\ exergy\ destruction \tag{2}$$

$$X = [\dot{m}_6\ \dot{m}_{12}\ T_7\ T_9\ P_{17}\ P_{19}\ P_{21}\ P_{23}\ P_{13}\ P_{10}] \tag{3}$$

where X is the variables vector, $\dot{W}$ represents net compression power, $\dot{m}_{LNG}$ is the mass flow rate of LNG stream, $\dot{m}_i$, T_i, and P_i are the mass flow rate, temperature, and pressure of stream i, respectively. Exergy destruction rate for process components was calculated based on the well-known equations summarized in Table 4 which can be found in the previous work [32].

Table 4. Definitions for exergy destruction rate of the process equipment.

Component, k	**Exergy of fuel** ($\dot{E}_{F,k}$)	**Tuning parameters** ($\dot{E}_{P,k}$)	**Exergy destruction** ($\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k}$)
Compressor	$\dot{W}_{COMP}$	$\dot{E}_{out} - \dot{E}_{in}$	$\dot{W}_{COMP} - \dot{E}_{out} + \dot{E}_{in}$
Expander	$\dot{E}_{in} - \dot{E}_{out}$	$\dot{W}_{EXP}$	$\dot{E}_{in} - \dot{E}_{out} - \dot{W}_{EXP}$
Heat Exchanger	$\sum\left(\dot{E}_{in} - \dot{E}_{out}\right)_{Cold}$	$\sum\left(\dot{E}_{out} - \dot{E}_{in}\right)_{Hot}$	$\sum\left(\dot{E}_{in} - \dot{E}_{out}\right)_{Cold} - \sum\left(\dot{E}_{out} - \dot{E}_{in}\right)_{Hot}$
Air Cooler	$\dot{E}_{in} - \dot{E}_{out}$	$\dot{E}^{air}_{out}$	$\dot{E}_{in} - \dot{E}_{out} - \dot{E}^{air}_{out}$
Total System	$\dot{E}_{F,total} = \sum \dot{W}_{COMP}$	$\dot{E}_{F,total} - \dot{E}_{D,total}$	$\dot{E}_{D,total} = Summation\ of\ irreversibility\ of\ all\ devices$

3.3. Decision variables and constraints

In LNG plants, compressors outlet pressure, exchangers outlet temperatures and refrigerant molar flow rate are the main operating variables affecting the objective functions. In this regard, the sensitivity of the objectives to the decision variables should be investigated in order to choose the most effective parameters. Results of the sensitivity analysis are presented in the Results and discussion section. Based on the results, ten influencing parameters were selected as decision variables including two molar flow rates, six pressures, and two temperatures. The variables change ±30% of base values during the optimization. Constraints associated with the optimization problem due to previous experiments and design limitations of liquefaction plants can be expressed as:

$$3 \le min.\,approach\ \big(E - (n)\big) \le 4 \quad (n = 1,2,3)$$

$$\left\{\frac{P_{17}}{P_{16}}, \frac{P_{19}}{P_{18}}, \frac{P_{21}}{P_{20}}, \frac{P_{23}}{P_{22}}\right\} \in [1,3]$$

$$Compressors\ outlet\ temperature \le 150\ °C \tag{4}$$

where n is number of the multi stream heat exchangers.

Table 5. Definition of the optimization problem.

	Baseline
Decision Variables	
Temperature of stream 7 (°C), x_1	-6
Temperature of stream 9 (°C), x_2	-89
Pressure of stream 17 (*kPa*), x_3	600
Pressure of stream 19 (*kPa*), x_4	1100
Pressure of stream 21 (*kPa*), x_5	2000
Pressure of stream 23 (*kPa*), x_6	4000
Pressure of stream 13 (*kPa*), x_7	550
Pressure of stream 10 (*kPa*), x_8	600
Molar flow of stream 6 (*kgmole/hr*), x_9	138.2
Molar flow of stream 12 (*kgmole/hr*), x_{10}	91.8
Constraints	
$3 \leq$ Minimum temperature approach of E-1 °C ≤ 4	
$3 \leq$ Minimum temperature approach of E-2 °C ≤ 4	
$3 \leq$ Minimum temperature approach of E-3 °C ≤ 4	
Temperature of outlet stream from compressors (°C) ≤ 150	
Pressure ratio of compressors ≤ 3	
Objective Functions	
Minimizing: Specific power consumption of the process (*kWh/kg LNG*)	
Minimizing: Total exergy destruction (*kW*)	

Table 5 summarizes the optimization problem details consist of the decision variables and their baseline values, constraints and objective functions.

4. Results and discussion

4.1. Baseline process

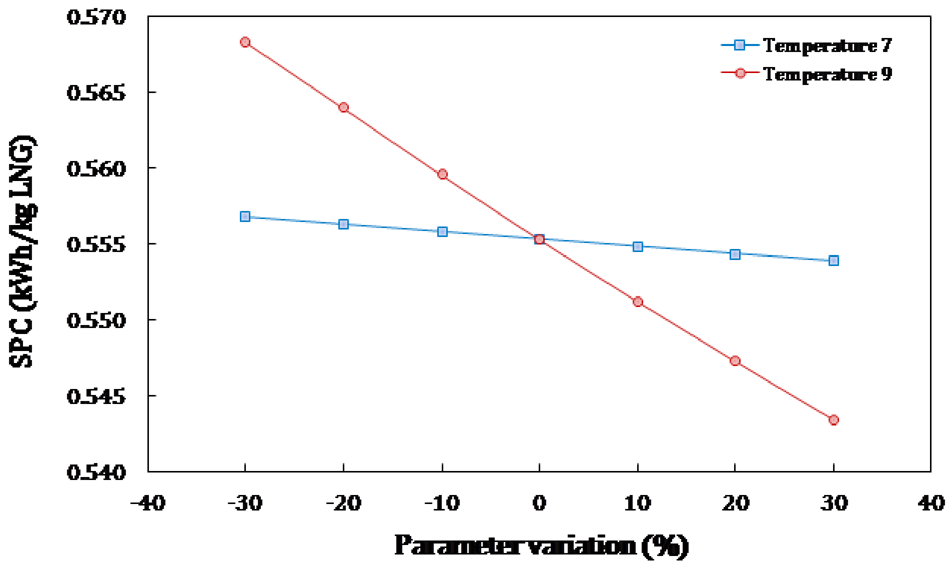
As explained before, BHP Billiton is a dual expander natural gas liquefaction process. In general, nitrogen expansion cycles consume larger power than mixed refrigerant ones; However, their structure and operation have less complexity. Therefore, some efforts have already been made to reduce the compression power by improving the structure or the operating conditions. In mixed refrigerant processes, the most important variable influencing energy performance is refrigerant composition [6,18,31] which is not the case in pure refrigerant expansion cycles. Thus, affecting parameters are restricted to refrigerant flow rate, maximum and minimum cycle pressures and intermediate temperatures. To perform further analyses and also optimize the process, the process simulation should be primarily validated. To this, some specifications obtained from the simulation such as specific power consumption and T-s diagram of the baseline liquefaction cycle can be compared with the basic concepts and previous works in the literature. Due to the results, SPC of the process was calculated 0.5553 kWh/kg LNG which satisfies conventional constraints [29]. Table 6 represents the thermodynamic performance of the main refrigeration cycle equipment. Adiabatic efficiencies for the compressors and the expanders were assumed 80% and 85% respectively which increase the capital cost at the expense of the operating cost and the process efficiency.

Table 6. Thermodynamic performance of the refrigeration cycle equipment.

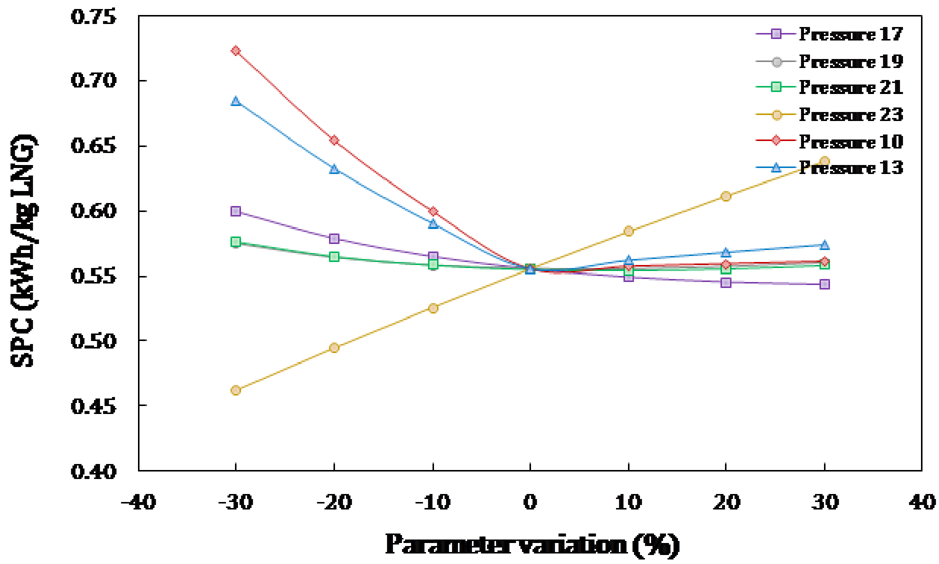
Stream No.	Power consumed (kW)	Adiabatic efficiency (η ,%)	Pressure ratio	Outlet temperature (°C)
C-1	36.97	80	1.33	69.24
C-2	95.69	80	2	124.78
C-3	88.32	80	1.9	118.37
C-4	99.68	80	2.05	128.38
	Power produced (kW)	**Adiabatic efficiency (η ,%)**	**Pressure ratio**	**Outlet temperature (°C)**
EXP-1	68.86	85	0.14	-108.2
EXP-2	20.42	85	0.16	-161.70
	Number of sides	**Cold duty (kW)**	**Min. approach (°C)**	**LMTD (°C)**
E-1	4	68.88	3.71	8.2
E-2	4	92.23	3.83	7.67
E-3	3	27.21	3.99	12.13
	Cold duty (kW)	**LMTD (°C)**	**UA (kW/°C)**	**Air Inlet Condition**
AC-1	33.04	26.93	1.23	25 °C , 1 atm
AC-2	96.99	44.5	2.19	25 °C , 1 atm
AC-3	90.59	42.64	2.13	25 °C , 1 atm
AC-4	104.46	45.53	2.3	25 °C , 1 atm

4.2. Sensitivity analysis

A useful method to determine effective parameters of an energy-intensive process, which should be used in optimization, is to analyze the sensitivity of process performance to operating variables. In a refrigeration cycle, maximum and minimum pressures, intermediate temperatures and refrigerant molar flow are the main operating variables. Hatcher et al. [19] carried out a sensitivity analysis to understand the impacts of operating variables on the process performance and to direct the formulation of the LNG plant optimization. Also, Wang et al. [3] performed the sensitivity analysis to identify the effect of varying the objective function coefficient of variables on optimal results. In the present study, a sensitivity analysis was carried out to identify the decision variables listed in Table 5. All the variables were changed ± 30% of their base values to analyze the impact of these changes on the selected objective functions of SPC, and total exergy destruction. Figs. 3(a) and 4(a) show the effect of temperature of streams 7 and 9 on SPC and $\dot{E}_D^{tot}$, respectively. As shown in Fig. 3(a), the objective decreases with increasing both temperatures because of a decrement in the minimum approach of E-2 and E-3 heat exchangers and consequently an improvement in thermal efficiency of the process. Fig. 4(a) shows that total exergy destruction increases with decreasing the temperature to -106.8 °C (-20% of baseline), then a reduction is observed. This behavior is originally related to the variation of the minimum temperature approach of E-2 and E-3 exchangers and irreversibility of EXP-2. The minimum approach of E-2 and the irreversibility of EXP-2 are increased with increasing the temperature from -30% to 30% of baseline. However, for E-3 exchanger, the minimum approach initially increases and then decreases with increasing the temperature which has a similar trend to that observed for $\dot{E}_D^{tot}$. This indicates that E-3 exchanger has a greater effect on total exergy destruction of the process. It can be found that both variables have a relative effect on the objectives and the temperature of stream 9 has a greater effect on both objectives. Figs. 3(b) and 4(b) illustrate the effect of outlet pressure of the compressors and the expanders on the objective functions. The similar trend can be observed for both diagrams. For compressors C-1, C-2 and C-3 (P_{17}, P_{19} and P_{21}), SPC and $\dot{E}_D^{tot}$ decrease slightly with increasing the outlet pressures. On the contrary, the objectives for C-4 (P_{23}) increased with increasing the outlet pressure. There is a different trend for expanders EXP-1 and EXP-2 (P_{10} and P_{13}) in SPC and $\dot{E}_D^{tot}$ diagrams that a sharp decrement is seen for pressures below the baseline and a mild increment is observed for pressures above the baseline. Figs. 3(c) and 4(c) represent the effect of molar flow rate of nitrogen refrigerant (stream 6) and refrigerant of high-temperature section (stream 12) on SPC and $\dot{E}_D^{tot}$. As expected, SPC and total exergy destruction increase with increasing the refrigerant molar flow. This is due to an increase in compressor powers and minimum temperature approach of the heat exchangers. In contrast, by increasing the flow rate of refrigerant used in high-temperature section (or decreasing the flow rate used in low-temperature section), both objectives are reduced. This might have originated from reducing the minimum approach of E-2 and E-3 heat exchangers and the irreversibility of EXP-2 with decreasing molar flow rate of stream 8.



(a)



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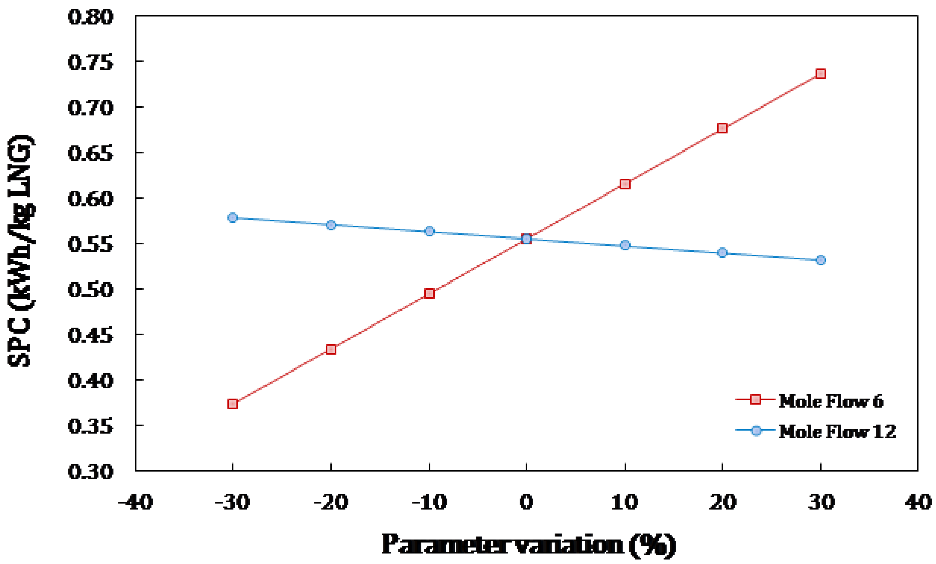
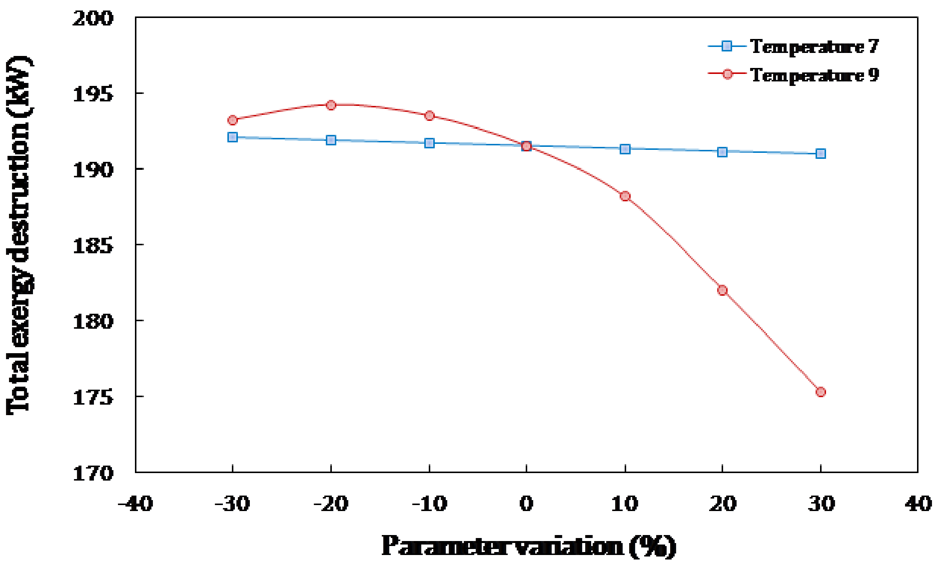
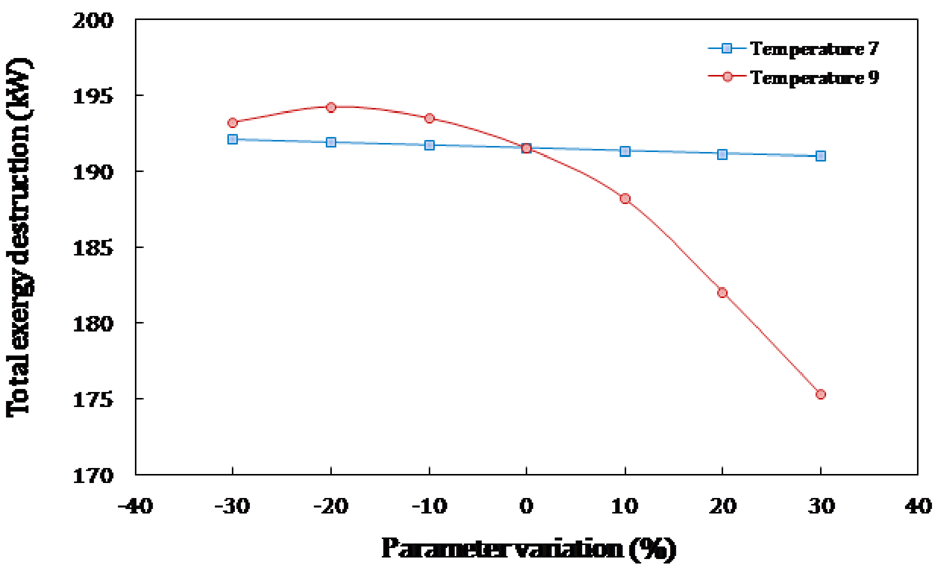


(c)

Fig 3. The effect of (a) temperatures, (b) outlet pressures and (c) molar flow rates on SPC.



(a)



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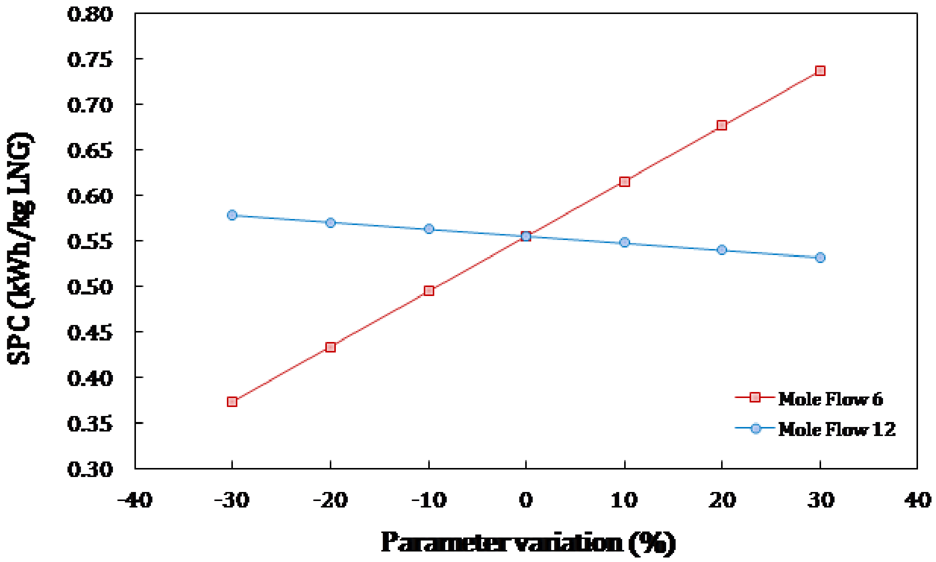


(c)

Fig 4. The effect of (a) temperatures, (b) outlet pressures and (c) molar flow rates on $\dot{E}_D^{tot}$.

Previous works can confirm the results of sensitivity analysis. Vatani et al. [32] and He and Ju [13] investigated the impact of such variables on SPC of some LNG processes and similar trends for refrigerant pressure, and molar flow rate are observed. It can be concluded from the results that the proposed operating variables have the similar effect on both objective functions of SPC and $\dot{E}_D^{tot}$.

4.3. Optimization results

In the present study, two objective functions which describe the performance of liquefaction process regarding energy quantity and quality were optimized separately through adjusting aforementioned operating variables by using genetic algorithm. The convergence curve of fitness value for the total exergy destruction against the generations is shown in Fig. 5. The same curve can be obtained for SPC which is not shown here to avoid repetition. The algorithm converges at the 69th generation. The optimal values of the decision variables are presented in Table 7. It is evident from the table that most of the variables are increased compared to the baseline values.

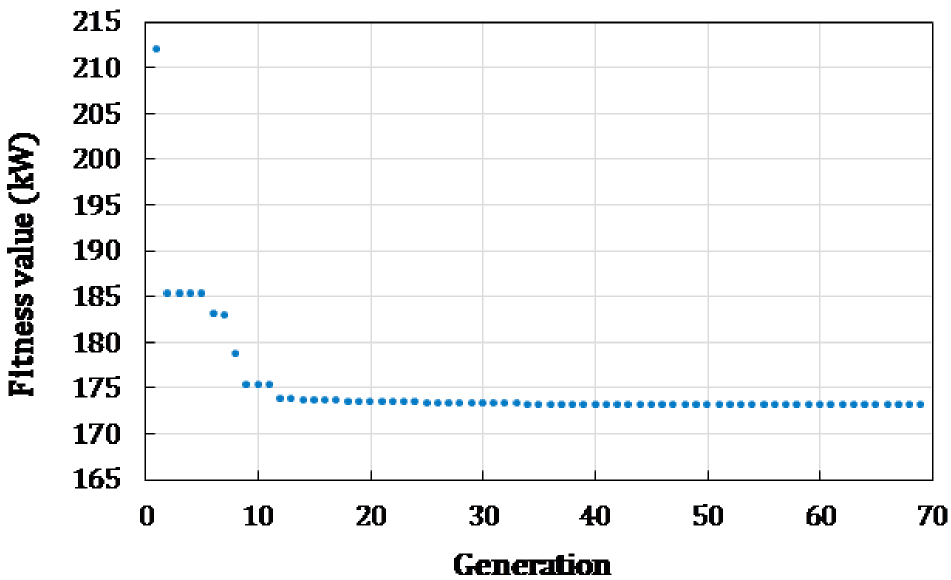


Fig 5. The convergence curve of the genetic algorithm for the total exergy destruction.

Table 7. The optimal values of the decision variables.

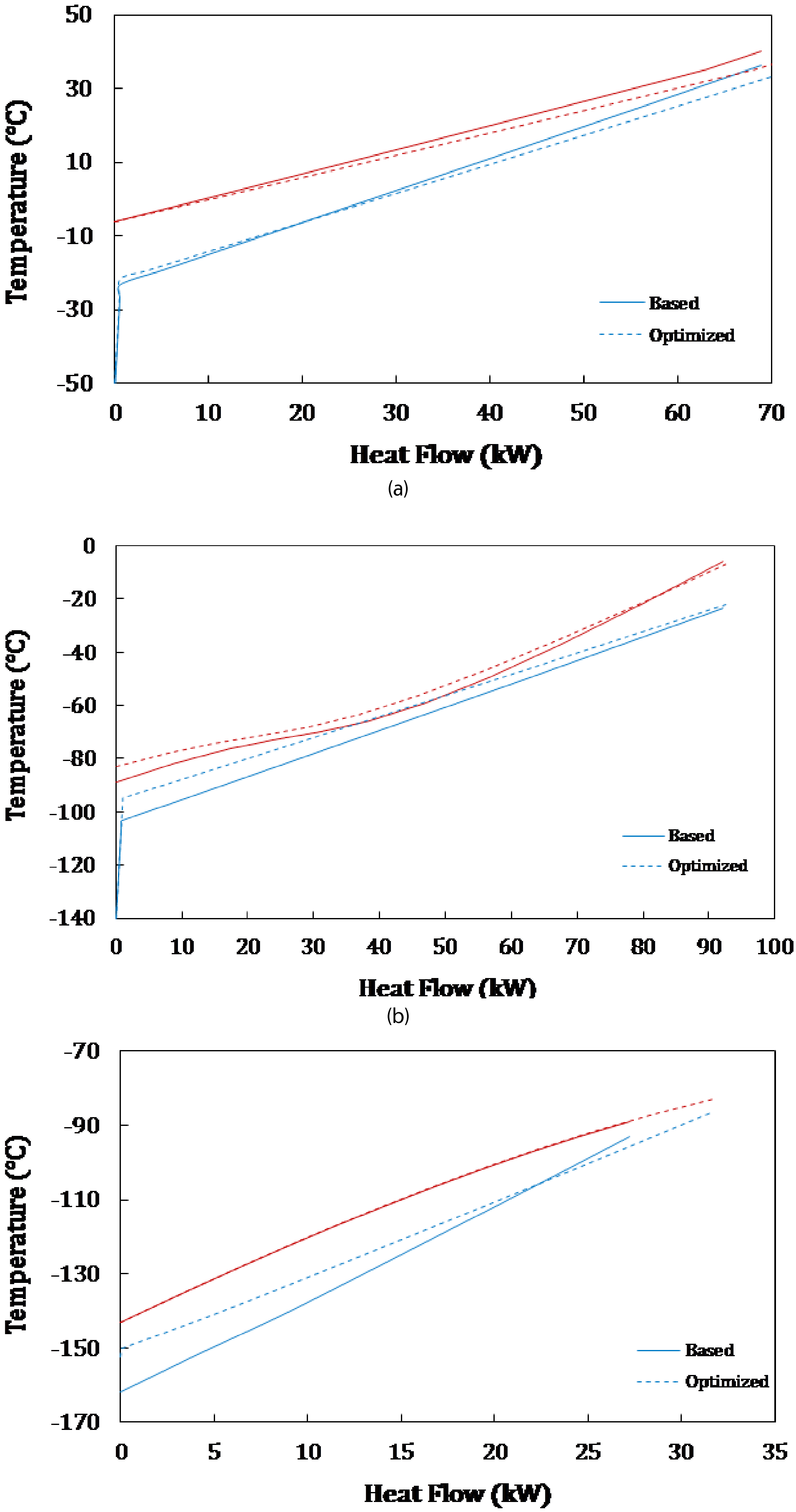
Variable	Baseline	Optimized	
		SPC case	$\dot{E}_D^{tot}$. case
x_1	-6	-4.25	-6.15
x_2	-89	-79.84	-83.14
x_3	600	779.98	779.91
x_4	1100	1310.74	1369.1
x_5	2000	2317.79	2408.61
x_6	4000	3955.93	4051.8
x_7	550	656.95	694.77
x_8	600	706.87	779.87
x_9	138.2	148.99	151.94
x_{10}	91.8	87.92	93.92

Table 8. Thermodynamic performance of the baseline and optimized liquefaction process.

Variable	BHP liquefaction process			Improvement (case 1 / case 2) (%)
	Based	Optimized-SPC	Optimized- $\dot{E}_D^{tot}$	
Total power consumption (kW)	231.38	214.96	214.94	7.1
Total cold duty (kW)	188.32	196.84	199.54	4.5 / 6
LNG mass flow rate (kg/hr)	416.67	416.67	416.67	-
COP	0.81	0.92	0.93	13.6 / 14.8
Total exergy destruction (kW)	191.53	175.02	173.23	8.6 / 9.6
SPC (kWh/kg LNG)	0.5553	0.5159	0.5159	7.1
Total exergy efficiency (%)	17.22	18.58	19.41	7.9 / 12.7

The main indicators of thermodynamic performance of the process are summarized in Table 8 for the base and optimized cases. As can be seen, total power consumption for both optimization cases reduce from 231.38 kW to 214.9 kW and by considering a constant value for the mass flow rate of LNG product, SPC of the process is also decreased to 0.5159 kWh/kg LNG which corresponds to 7.1%. This shows a significant improvement in SPC for both cases. Total cold duty of the liquefaction cycle increases from 188.32 kW for baseline process to 196.84 and 199.54 kW for optimized-SPC and optimized-$\dot{E}_D^{tot}$ which corresponds to 4.5% and 6% improvement, respectively. Also, COP of the cycle improves 13.6% for optimized-SPC and 14.8% for optimized-$\dot{E}_D^{tot}$ processes which can be attributed to the increment in total cold duty and the simultaneous decrement in total power consumption. These improvements in COP values of the liquefaction cycle display a more favorable thermodynamic performance of the optimized process than the baseline. A remarkable result is observed for the value of total exergy destruction in two optimization cases. As can be seen, $\dot{E}_D^{tot}$ is reduced 8.6% and 9.6% for optimized-SPC and optimized-$\dot{E}_D^{tot}$ cases, respectively. The value of the total exergy destruction for optimized-$\dot{E}_D^{tot}$ is less than the other case while SPC is equal for both. The total exergy efficiency of the process which can be calculated using Eq. (5) [32] (7.9% and 12.7% improvement) also displays a similar trend. Therefore, it can be concluded from these results that in the same situations, the optimization with total exergy destruction as the objective function shows more appropriate results regarding both quantity and quality of energy consumption.

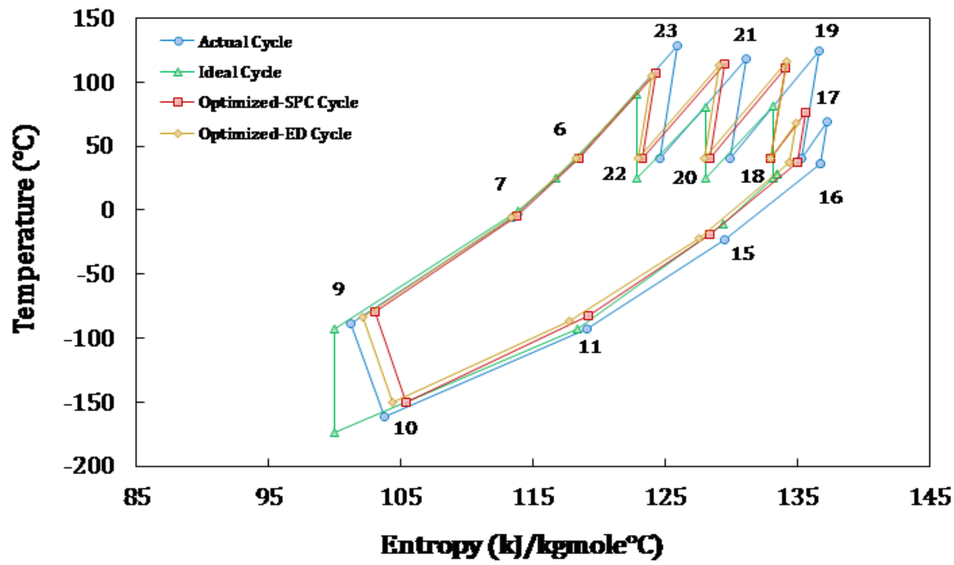
$$\varepsilon_{tot} = 1 - \frac{total\ exergy\ destruction}{total\ power\ consumption} \quad (5)$$



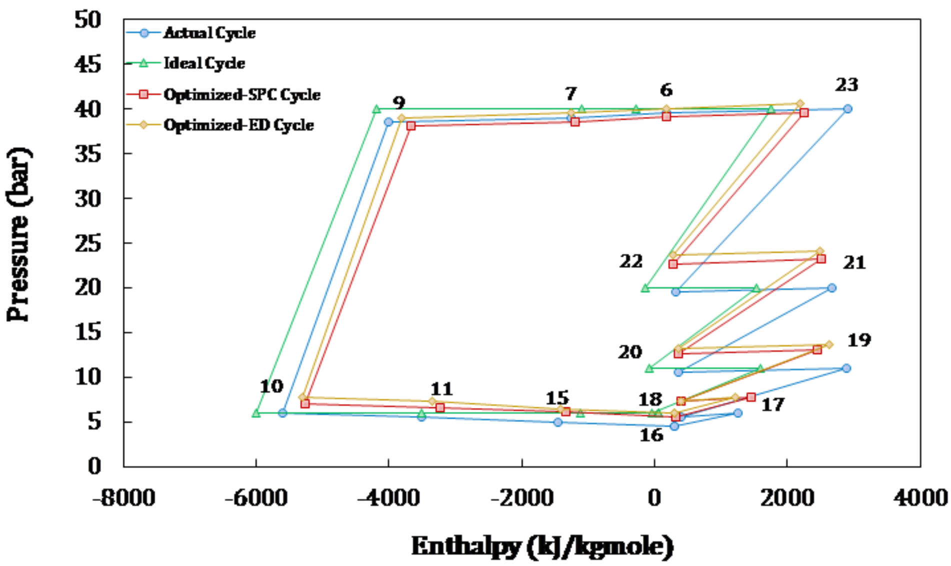
(c)

Fig 6. Composite curves of (a) E-1, (b) E-2 and (c) E-3 heat exchangers for baseline and optimized cycles in $\dot{E}_D^{tot}$ case.

Fig. 6 illustrates the composite curves of the multi stream heat exchangers (E-1, E-2 and E-3) for baseline and optimized cycles in $\dot{E}_D^{tot}$optimization case. As displayed, the cold curve in the optimized process is closer to the hot curve than the baseline cycle, especially for E-3 heat exchanger which reveals the improvement obtained in the optimization study. Since heat transfer across a finite temperature difference is a source of irreversibility [5], thus total exergy destruction and specific power consumption of the process will be reduced along a more efficient heat transfer while the minimum approach of heat exchangers decreases. Alabdulkarem et al. [18] applied a GA optimization to a C_3MR LNG process, and they concluded from the results that the cold curve of the optimized cycle is closer to the hot curve than the baseline cycle, which means more efficient heat transfer or less entropy generation in the heat exchanger. Also, Moein et al. [14] carried out a GA optimization on an SMR LNG process and confirmed that total required power decreases about 14% due to a decrement in heat exchanger temperature difference.



(a)



(b)

Fig 7. (a) T-s and (b) P-h diagrams of the actual, ideal and optimized liquefaction cycles.

Comparison of actual and ideal performance of the liquefaction cycle through T-s and P-h diagrams shows the difference between current and ideal situation of energy in the process. Figs. 7(a) and 7(b) show T-s and P-h diagrams of the liquefaction cycle for actual, ideal and optimized cases, respectively. These diagrams indicate that thermodynamic performance of the cycle is exactly adapted with similar dual expander cycles found in the previous works [8,28]. On the P-h diagram, main processes of the liquefaction cycle (compression, cooling, expansion and evaporation) appear as straight lines and the heat transfer in the air cooler and the evaporator is proportional to the lengths of the corresponding process curves. However, when studying the second-law aspects of processes, entropy is commonly used as a coordinate on diagrams such as the T-s diagram [5]. In other words, the P-h and T-s diagrams can reveal useful data about the liquefaction cycle in terms of energy quantity and quality, respectively. As said before, these diagrams can indicate validation of the process simulation. T-s diagram of the baseline process shows a reasonable behavior of the liquefaction cycle. As shown in Fig. 7 (a), T-s diagrams of the liquefaction cycle after optimization with both objectives are closer to the ideal diagram which shows an improvement in cycle efficiency and a reduction in entropy generation. Considering Table 8 and Fig. 7 (b), the optimization has improved energy consumption and efficiency of the cycle, simultaneously. The T-s diagram also indicates that the improvement of energy efficiency in case of $\dot{E}_D^{tot}$ is larger than the SPC case. Thermodynamic diagrams of liquefaction processes have been commonly used for investigating their energy performance. Ding et al. [24] used T-s diagram to compare two novel structures for LNG production with well-known MFC process. By analyzing the heat transfer and thermodynamic performances, they proposed the configuration with a precooling cycle with three pressure levels, liquefaction, and subcooling with one pressure level as the most efficient and optimal process. As can be seen in Fig. 7 (b), optimization causes to increase the intermediate pressures in compression section. As a result, pressure ratio of the compressors will be closer to each other. This may be attributed to the fact that the pressure ratio across each stage must be the same to minimize compression work during multistage compression [5]. When optimizing specific power consumption of the process, the aim of optimization is only reducing the energy quantity regardless the quality, thus, the pressure ratios become as close as possible while the energy consumption decreases. In other words, the most important way for reducing SPC in liquefaction cycles with multistage compression section is to adjust similar pressure ratios for all the compressors. However, this principle is not considered alone when the aim of optimization is to enhance quality of energy consumption. Therefore, by considering Table 8 and Fig. 7(a) and 7(b), it can be concluded that while the pressure ratios are closer in case of SPC, the optimized-$\dot{E}_D^{tot}$ process presents a more efficient performance.

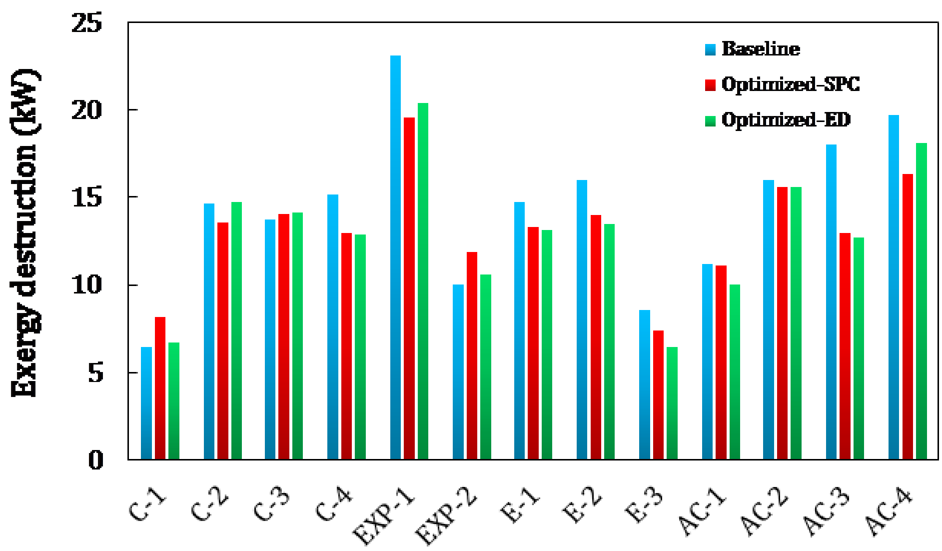


Fig 8. Exergy destruction of the process equipment for the baseline and optimized processes.

In order to investigate the effect of optimization on the quality of energy consumption in the process, exergy destruction of the process components and total exergy destruction and efficiency of the whole process should be analyzed. Fig. 8 represents the exergy destruction of the process equipment for the baseline and optimized processes . As can be seen in this figure, the irreversibility produced by most of the components reduces through optimization except for C-1, C-3 and EXP-2 which have larger exergy destruction after optimization. Increasing the irreversibility of C-1 and C-3 is directly originated from increasing outlet pressures to close the pressure ratios in $\dot{E}_D^{tot}$ case. Since the inlet molar flow rate of EXP-2 increases during optimization, more power is required and irreversibility increases.

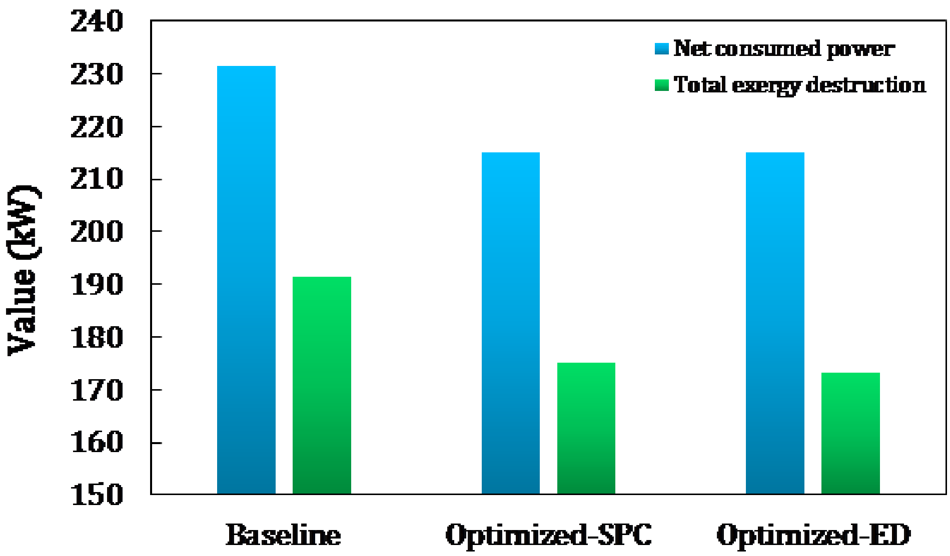


Fig 9. Total exergy destruction and net consumed power of the baseline and the optimized liquefaction processes.

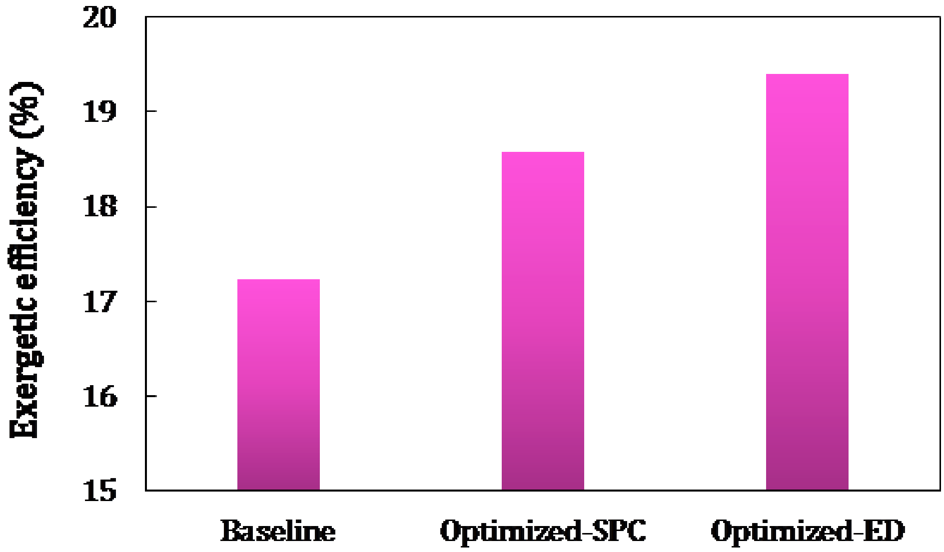


Fig 10. Total exergy efficiency of the baseline and the optimized liquefaction processes.

Overall results of applying the GA procedure to BHP natural gas liquefaction process for energy and exergy optimization are presented in Figs. 9 and 10, respectively. Fig. 9 compares total exergy destruction and net consumed power for the baseline and the optimized liquefaction processes. As figure shows, net consumed power was reduced to 214.9 kW for both optimized cases. However, total exergy destruction of the optimized-$\dot{E}_D^{tot}$ process decreased to 173.23 kW which is slightly less than optimized-SPC case (175.02 kW). The difference between these two optimization cases is evident in Fig. 10 in which total exergy efficiency of the baseline and optimized processes are compared. This figure demonstrates that total exergy efficiency of the optimized-$\dot{E}_D^{tot}$ and optimized-SPC is 19.41% and 18.58%, respectively, while specific power consumption and even total exergy destruction of both cases (Fig. 9) have approximately the same reduction rather than the baseline process. Therefore, selecting the second-law aspect of energy consumption (quality or work potential of energy) in the form of total exergy destruction as an objective function decreases SPC of the baseline to the same level of the optimized-SPC case while total exergy efficiency of the optimized-$\dot{E}_D^{tot}$ case is 4.4% larger than the optimized-SPC case. Such results can prove the hypothesis considered at the beginning of the present study.

Many studies have been reported in the literature about optimization of a wide variety of natural gas liquefaction processes. As mentioned further, most of them are related to the mixed refrigerant processes, and there are a few studies on single or dual nitrogen expander ones. A summary of recent optimization works applied to single or dual nitrogen expander processes is presented in Table 9. Optimization approach, objective functions, main constraints, based and optimized values of the objectives and percent of improvement are provided for each study. It should be noted that operating variables of almost all studies are similar to the present work.

Table 9. Comparison of optimization results of this study and previous works.

Process	Main constraints	Objective function	Optimization approach	Based value	Optimized value	Improvement (%)	Reference
Small-scale dual nitrogen expander	$\Delta T_{min} > 3$ Compressor pressure ratio < 3	Unit energy consumption (kWh/Nm^3)	Genetic algorithm	0.5417	0.5163	4.69	[8]
Small-scale single nitrogen expander	$\Delta T_{min} > 2$ Compressor pressure ratio < 3	Unit energy consumption (kW/kmol/h)	HYSYS optimization package	-	9.9	-	[26]
Small-scale dual nitrogen expander	$\Delta T_{min} > 3$	Compression energy requirement (kWh/kg LNG)	Knowledge inspired investigation	-	0.5007	-	[27]
Dual nitrogen expander	$\Delta T_{min} > 3$ Compressor pressure ratio < 3 $T_{OR}{}^a = T_{DR}{}^b + 3$	Figure of merit	Genetic algorithm	-	0.566	-	[28]
Single nitrogen expander	ΔTmin > 2 Compressor pressure ratio < 3	Unit energy consumption (kW/kmol/h)	Genetic algorithm	9.9	8.9	10.1	[29]
This work	$3 < \Delta T_{min} < 4$ Compressor pressure ratio < 3 Compressor outlet temperature < 150	Specific power consumption (kWh/kg LNG)	Genetic algorithm	0.5553	0.5159	7.1	-
		Total exergy destruction (kW)			173.23	9.55	

a. Temperature of the outlet refrigerant

b. Dew point of the outlet refrigerant

By comparing the results of the present work and previous studies, it is revealed that optimization of the liquefaction process using the genetic algorithm approach could improve energy performance regarding quantity and quality. As can be seen in Table 9, total exergy destruction is not considered as an objective function of any of the studies. He and Ju [8] adjusted some operating variables to minimize the unit energy consumption (kWh/Nm^3) of a dual nitrogen expander process. The objective function was reduced 4.69% using the GA approach. This result shows a significant predominance of the present work compared to the mentioned study. Also, Song et al. [29] optimized the unit energy consumption (kWh/kmol) of another single nitrogen expander process utilizing modified the GA optimization tool, and the objective function is eventually reduced 10.1% in the best situation. This result may attribute to the larger power consumption of single expander processes rather than dual expander ones which displays an enormous potential for improvement in optimization efforts.

5. Conclusions

In this study, a mini-scale nitrogen dual expander natural gas liquefaction process was simulated and analyzed by Aspen HYSYS simulator. Then, it was optimized using the genetic algorithm approach provided by MATLAB software in two separate optimization cases with different objective functions. Specific power consumption and total exergy destruction of the process were taken as the objectives. The main decision variables, refrigerant molar flow, refrigerant outlet temperature of heat exchangers and refrigerant outlet pressure of compressors and expanders, were selected through a sensitivity analysis which was carried out on the baseline process. The results showed that the specific power consumption of the process is reduced to 0.5159 kWh/kg LNG (7.1% less than the baseline) and the total exergy destruction for the optimized-$\dot{E}_D^{tot}$ case decreases to 173.23 kW (9.55% less than the baseline) which is slightly a more desirable result compared with the optimized-SPC case. However, total exergy efficiency of the process in optimized-$\dot{E}_D^{tot}$ case is 4.4% higher than the other case. This reveals that for a similar quantity of energy, optimized-$\dot{E}_D^{tot}$ has a higher quality of energy and thus, considering the quality aspect of energy consumption as the objective can improve the performance of the process more appropriately.

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بهینه‌سازی انرژی و اکسرژی یک فرآیند کوچک‌مقیاس مایع‌سازی گاز طبیعی از نوع چرخه انبساطی نیتروژن

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چکیـــــده

فرآیندهای انبساطی نیتروژن، به دلیل سادگی و تجهیزات کم، برای واحدهای مایع سازی گاز طبیعی در مقیاس کوچک و بسیار کوچک (مینی) مناسب هستند. با این حال، مصرف بالای انرژی در این فرآیندها، هر تلاشی در زمینه کاهش مصرف انرژی و نیز ارتقاء کیفیت انرژی (ظرفیت کاردهی انرژی) را برای افزایش راندمان و سودآوری فرآیند، مطلوب می نماید. در این تحقیق، یک فرآیند مایع سازی گاز طبیعی از نوع انبساطی نیتروژن با دو توربین با نرم افزار اسپن هایسیس شبیه سازی گردیده و مورد تحلیل قرار گرفت. سپس به منظور بهینه سازی مصرف انرژی در فرآیند، برخی متغیرهای عملیاتی تأثیرگذار، با استفاده از الگوریتم ژنتیک و در محیط نرم افزار متلب تنظیم گردیدند. مصرف ویژه انرژی و مجموع نرخ تخریب اکسرژی که به ترتیب گویای کمیت و کیفیت مصرف انرژی در فرآیند می باشند، توابع هدف بهینه سازی هستند که در دو حالت جداگانه (حالت انرژی و حالت اکسرژی) بهینه می شوند. دبی مولی مبرد، دماها و فشارهای پایین و بالای مبرد در چرخه، مهمترین پارامترهای عملیاتی تأثیرگذار می باشند که با تحلیل حساسیت انتخاب شدند. نتایج نشان داد که در هر دو حالت بهینه سازی، مصرف ویژه ۷/۱ درصد کاهش یافت. اما مجموع نرخ تخریب اکسرژی در حالت اکسرژی، تا ۹/۵۵ درصد کاهش پیدا کرد. همچنین راندمان اکسرژی کل فرآیند در حالت اکسرژی تا ۴/۴ درصد بیشتر از حالت انرژی است که این امر نشان دهنده برتری انتخاب کیفیت مصرف انرژی به‌عنوان تابع هدف بهینه سازی است

واژگان کلیدی: Liquefied natural gas, Nitrogen expansion, Optimization, Energy, Exergy destruction, Efficiency.

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