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Genetic algorithm optimization of two natural gas liquefaction methods based on energy, exergy, and economy analyses: the case study of Shahid Rajaee power plant peak-shaving system

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Abstract: Power plants have problems supplying fuel in the cold season due to the high domestic demand for natural gas. Therefore, they use alternative fuels such as diesel and fuel oil, which reduce the plant's efficiency and cause environmental problems. Fuel peak-shaving is a solution that means liquefaction and storage of natural gas in hot seasons and then using it in cold seasons. Two cycles of the PRICO and LIMUM3 liquefaction methods, which are the two most peak-shaving cycles in natural gas liquefaction, have been studied and optimized for the case study Shahid Rajaee power plant in Qazvin city, Iran. By performing energy, exergy, and economy analyses, these two cycles are compared. A genetic algorithm is used to optimize and find the appropriate values of the key parameters. Using optimization, the SEC value in PRICO and LIMUM3 cycles experienced +0.15 and +0.12 improvement, respectively. PRICO with SEC value of 0.268 performed better than the other cycle with a value of 0.317. The annual capital expenditure (CAPEX) of the PRICO cycle was 9.12 million $, which is higher than the other cycle by 7.58 million $. The annual cost of operation (OPEX) is saved in the PRICO cycle due to the lower SEC and power consumption. The annual total cost of PRICO is 23.81 million $, which is 6.1% less than that of the LIMUM3 cycle. Finally, by comparing the results, the PRICO cycle was found to be more suitable than LIMUM3 for the peak-shaving of the Shahid Rajaee power plant.

keywords: LNG, Mixed Refrigerant, Peak-shaving, Economy Analysis, Exergy Analysis

Introduction

Iran is one of the largest natural gas reservoir owners and has a wide local distribution network. The problem of high consumption of natural gas in cold seasons and the pressure drop of gas has led to alternative fuels such as fuel oil, which has many environmental problems. According to the Iranian Environmental Protection Organization, in February 2018, 440,000 barrels of fuel oil were burned daily in the country's power plants, which is very dangerous due to the phenomenon of air inversion. According to the National Iranian Gas Company's announcement in 2018, 5 billion and 238 million cubic meters of gas have been consumed in various industrial and domestic sectors of Qazvin province, while the need for Shahid Rajaee power plant wat 2 billion and 634 million cubic meters. It is 0.51 of the total consumption of the province (Hojajizadeh, 2015). The ratio of energy to the natural gas volume at ambient pressure and the temperature is low; therefore, natural gas storage in hot seasons occupies a large volume. The solution is to reduce the natural gas temperature until it liquefies (Zhang, Meerman, Benders, & Faaij, 2020).

Natural gas liquefaction and storage near power plants or at the original distribution units can solve the lack of natural gas fuel in cold seasons. An important challenge in expanding the liquid natural gas (LNG) industry is the liquefaction process's energy-consuming. Regasification, which is accompanied by heating and turning liquid into gas, causes a waste of energy, which also uses various methods to minimize the power in compression parts of LNG processes.

In recent years, some research has been done to improve the performance of natural gas liquefaction cycles. Nguyen et al. (Nguyen, Rothuizen, Markussen, & Elmegaard, 2018) studied three mixed refrigerant

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methods, including simple and two-stage Brayton systems. Different feed gas compositions and refrigerant properties were investigated; the most suitable cycle design was determined by optimization. Mehrpooya & Ansarinasab (Mehrpooya & Ansarinasab, 2015) analyzed two simple mixed-component refrigerant processes by exergy and exergoeconomic analyses. They also explored the relationship between capital and operation costs and introduced the devices with the highest exergy destruction cost. Finally, economic optimization methods based on sensitivity analysis for exergoeconomic factors and exergy destruction cost were introduced. Serkani and Mafi(Fazlali Serkani & Mafi, 2020) studied the peak-shaving of a 332 MW power plant and examined the use of nitrogen expanders in this power plant. Also, they investigated the effect of feed gas composition on the performance of cycles in peak-shaving by using sensitivity analysis. Although they optimized feed gas composition, more variables could be optimized in future researches.

Khodaei et al. (Khodaee, Ashrafizadeh, & Mafi, 2017) simulated the propane and butane gas liquefaction unit with ASPEN HYSYS software and used a genetic algorithm to optimize it. They found the minimum power consumption of the liquefaction cycle. Moradi et al. (Moradi, Mafi, & Khanaki, 2015)investigated the proposed cycles to store natural gas near power plants and calculated these cycles' required capacity in Iran. They determined the performance parameters and studied the different country's feed gas compositions' environmental and operational effects.

Aslambakhsh et al. (Aslambakhsh, Moosavian, Amidpour, Hosseini, & AmirAfshar, 2018)simulated and analyzed a small natural gas-scale liquefaction unit with a capacity of 50 tons per day and optimized it using a genetic algorithm. Ghorbani et al. (Ghorbani, Shirmohammadi, Mehrpooya, & Hamedi, 2018) used a genetic algorithm to optimize a cryogenic natural gas process. Linde Company proposed LIMUM1 and LIMUM3 cycles to liquefy natural gas. The LIMUM3 process includes four stages of cooling. LIMUM3 is more complicated than LIMUM1. The mixed refrigerant method is used in both cycles. LIMUM1 is used in low capacity LNG production processes, under 1600 TPD, while the performance of LIMUM3 is appropriate in large capacity cycles (Mazyan, Ahmadi, Ahmed, & Hoorfar, 2016)

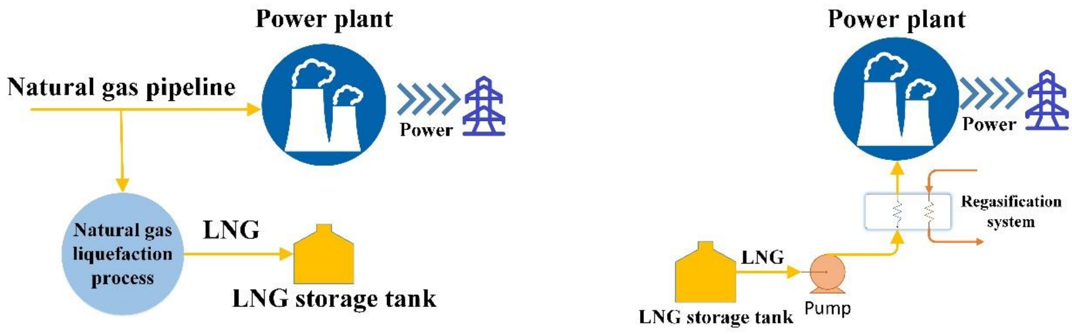
Lin et al. (Lin, Xiong, & Gu, 2018) investigated a new cascading cycle of high-pressure natural gas with a new carbon dioxide cryogenic separation unit. In the new cycle, instead of using the conventional three-tier system, a two-tier cascading system was used, and also three new refrigerant combinations were used to reduce specific energy consumption. Moreover, they did energy analysis and thermodynamic optimization. Watson et al. (Watson, Vikse, Gundersen, & Barton, 2018)studied natural gas liquefaction cycles with single-stage multi-component refrigerants strategies for the optimal heat exchange surfaces in heat exchangers. They introduced multi-stream heat exchangers to reduce irreversibility. Wang et al. (Wang et al., 2019)experimentally investigated the natural gas liquefaction cycle with the mixed refrigerant method. The effect of operational pressures and refrigerant flow compositions on cycle performance was investigated.

Ghorbani et al. (Ghorbani, Roshani, Mehrpooya, Shirmohammadi, & Razmjoo, 2020) analyzed and modified the cryogenic natural gas unit. Exergoeconomic and advanced exergy analyses were used to identify the most irreversible exogenous and endogenous devices. By increasing the efficiency of these devices, they reduced the total exergy destruction. Khan et al. (Khan, Lee, & Lee, 2012) investigated the use of refrigerants containing nitrogen, methane, ethane, and propane to liquefy natural gas. Using a modified PRICO system, the power was reduced. Ghorbani et al. (Ghorbani, Javadi, Zendehboudi, & Amidpour, 2020; Ghorbani, Miansari, Zendehboudi, & Hamedi, 2020) examined economic analyses for natural gas liquefaction cycles.

There were many studies in the literature on natural gas liquefaction systems, but optimizing a natural gas fuel peak-shaving system for a power plant is a gab that needs more research to work on it. The novelty of this study is proposing and optimizing a new peak-shaving process suitable for a power plant. The optimization method is based on a genetic algorithm. In previous researches, there was not a comprehensive economic analysis on peak-shaving systems; therefore, economic analysis is performed on the proposed cycle in this study. The main objective of the present study is the selection of a suitable peak-shaving system for a power plant. Fuel peak-shaving leads to prevent replacing natural gas fuel with alternative fuels such as fuel oil and diesel, thereby causing environmental problems to decrease. In this research, the fuel peak-shaving of Shahid Rajaee power plant in Qazvin city has been studied using two methods, PRICO and LIMUM3. The two LNG production methods have been modified according to the Shahid Rajaee case study's detail. Energy, exergy, and economic analyses are used.

Process description

Shahid Rajaee power plant has a capacity of 2042 MW. The steam part includes four units of 250 MW with a total production capacity of 1000 MW, and the combined cycle part includes six gas units of 123.4 MW and three units of steam 100.6 MW with a capacity of 1042.2 MW. The efficiency percentages of the steam cycle and the combined cycle are 45.4 and 37.1, respectively. The number of peak days of natural gas fuel consumption is 60 days, and the number of non-peak days of consumption is 200 days (Katal & Fazelpour, 2018). According to this power plant's capacity and efficiency, the amount of 355336 tons of LNG is required for cold seasons. The natural gas liquefaction unit with a 0.025 percent higher capacity must have a production capacity of at least 119000 Kg/hour of LNG. First of all, PRICO and LIMUM3 cycles are simulated based on the fuel required by the Shahid Rajaee power plant and optimized by a genetic algorithm. PRICO and LIMUM3 are shown in Fig. 1. The appropriate cycle designed for power plant peak-shaving is identified by energy, exergy, and economic analyses in the final stage. The Block diagram of the power plant peak-shaving system is shown in Fig. 1, including peak and non-peak conditions.



(a) (b)

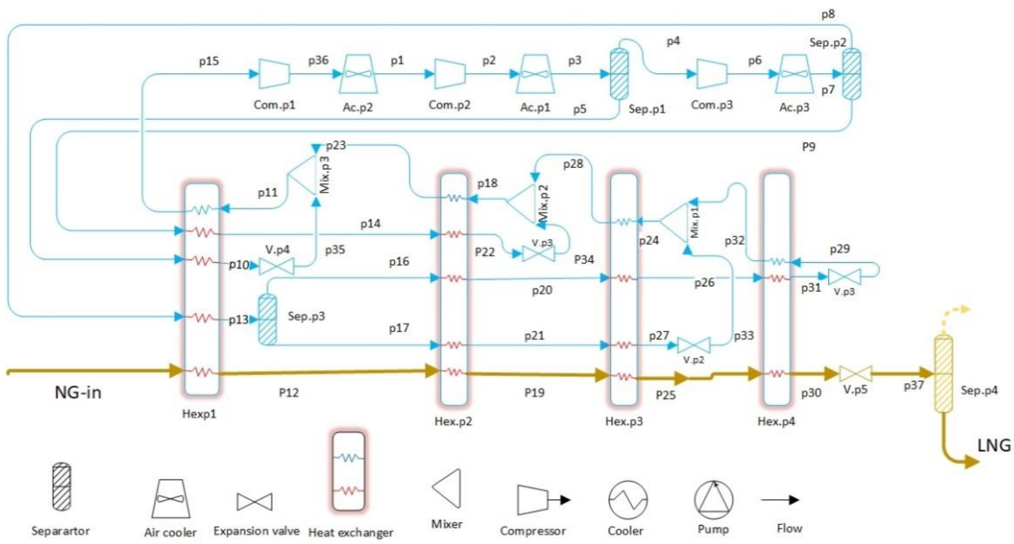
Fig. 1. **Power plant peak-shaving block diagram: (a) Non-peak condition, (b) Peak condition.**

Shown in Fig. 1(a) is the natural gas liquefaction cycle in non-peak conditions. The number of non-peak days is 200 per year. After entering the liquefaction cycle, natural gas is liquefied and stored in special tanks. Fig. 1(b) shows the peak-shaving process in peak conditions. In 60 days of the year, fuel demand increases significantly. After evaporating, liquefied natural gas is used during the 60 days.

LIMUM3 cycle is shown in Fig. 2(a) and 2(c). The mixed refrigerant stream exits the Hex.p1 heat exchanger and enters the compressors and air coolers. Passing two compressors and two air coolers, it enters the separator Sep.p1, where the liquid phase goes to the heat exchangers named Hex.p1, and the gas phase enters the Com.p3. After passing through the Hex.p1 heat exchanger, the P13 stream goes to the Sep.p3, in which the gas and liquid phases are separated. After passing Hex.p2, Hex.p3, and Hex.p4, it enters the V.p3 expansion valve, and the stream pressure witnesses a significant decrease, ending to 300 kPa. The natural gas stream is pre-cooled in Hex.p1, and in the second heat exchanger Hex.p2, the temperature reaches -70℃. Liquefaction starts in the third heat exchanger named Hex.p3. It is completely liquefied in Hex.p4. After passing through the V.p5 expansion valve, it reaches -164.6 ℃ and 300 kPa. Sep.p4 is used to separate LNG to store in cryogenic tanks (Pérez & Díez, 2009).

Turning to the PRICO cycle's detail in Fig. 2(b) and Fig. 2(d), the cold stream enters the HexM1 heat exchanger to cool down hot streams and then evaporates while leaving it. The pressure of this stream increases to 1023 kPa in the first compressor. A sharp rise of temperature happens in compressors, so coolers are utilized to cool the stream to 20 ℃. A pump is used to increase the liquid pressure, while a compressor increases the gas pressure up to 4050 kPa. The high-pressure stream enters the HexM1 heat exchanger. The outlet pressure and temperature of VM1 are 255 kPa and -165.9 ℃, respectively. Natural gas enters the heat exchanger at ambient temperature and pressure of 6000 kPa and then cools to -164.2 ℃. SepM1 is used to separate LNG from natural gas (Marmolejo-Correa & Gundersen, 2012).

Tables 1 and 2 show the stream properties and compositions of PRICO and LIMUM3 cycles. Feed natural gas composition in this study is the same as the fuel of Shahid Rajaee power plant in Qazvin. Table 1 shows the stream properties of PRICO and LIMUM3 cycles.



(a)

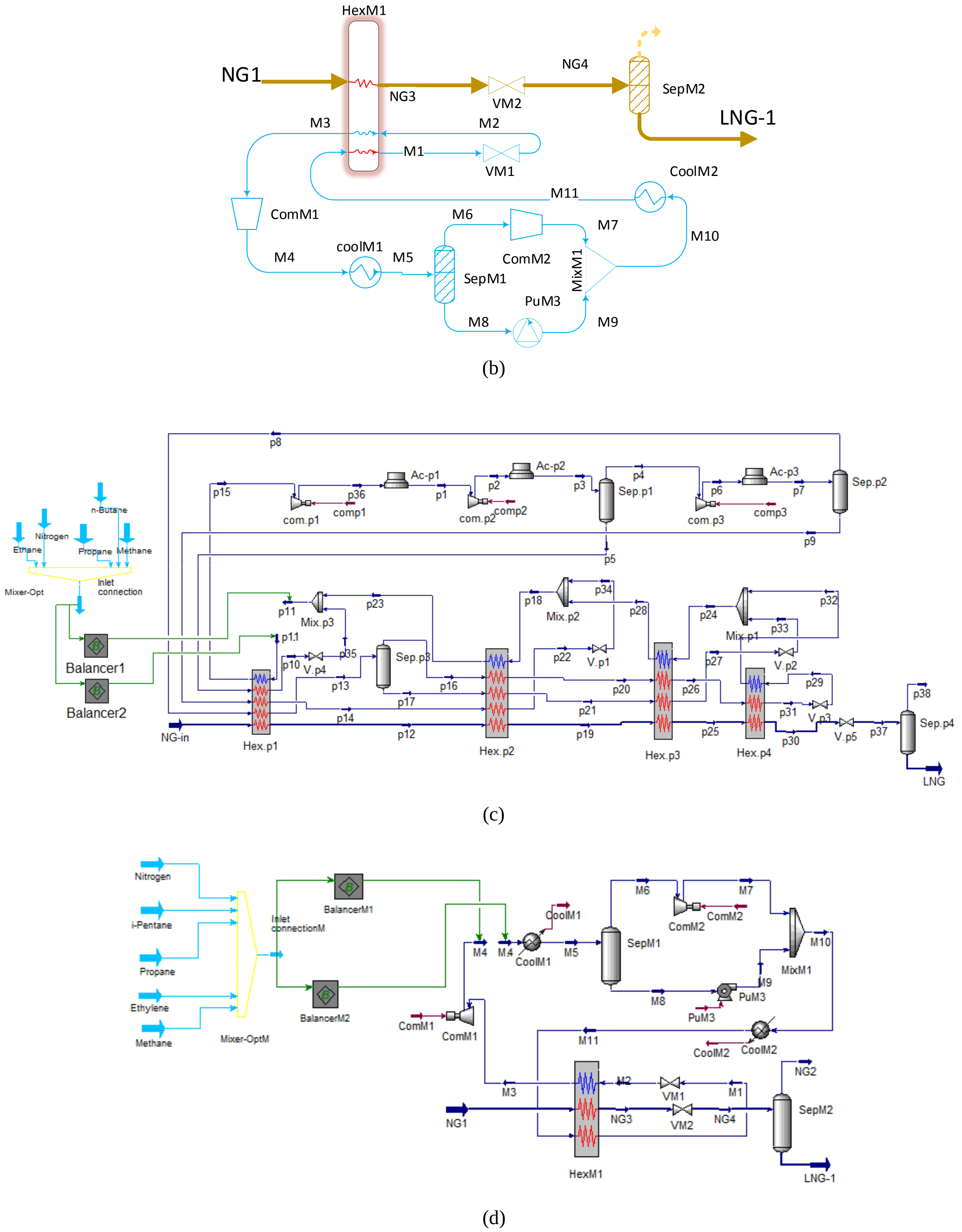


Fig. 2. LIMUM3 and PRICO process diagrams ;(a) LIMUM3 flow diagram, (b) PRICO flow diagram, (c) LIMUM3 HYSYS diagram, (d) PRICO HYSYS diagram.

Table 1. Stream information

Stream	Vapor fraction	P (kPa)	T (℃)	Mass flow(kg/h)	Stream	Vapor fraction	T (℃)	P (kPa)	Mass flow(kg/h)
LNG-1	0.00	101	-167	119023	p13	0.50	-3	4700	311923
NG3	0.00	6000	-164	126000	p14	0.00	-3	4700	201615
NG4	0.05	101	-167	126000	p15	1.00	34	300	522954
NG1	1.00	6000	20	126000	p16	1.00	-3	4700	129004
NG2	1.00	101	-167	6977	p17	0.00	-3	4700	182919
M1	0.00	4000	-160	482000	p18	0.48	-71	300	513538
M2	0.13	255	-166	482000	p19	0.00	-70	6000	130000
M3	1.00	255	19	482000	p20	0.35	-66	4700	129004
M4	1.00	1023	100	482000	p21	0.00	-66	4700	182919
M5	0.88	973	20	482000	p22	0.00	-50	4700	201615
M6	1.00	973	20	380346	p23	0.88	-35	300	513538
M7	1.00	4050	112	380346	p24	0.50	-89	300	311923
M8	0.00	973	20	101654	p25	0.00	-87	6000	130000
M9	0.00	4050	21	101654	p26	0.11	-84	4700	129004
M10	0.96	4050	76	482000	p27	0.00	-78	4700	182919
M11	0.60	4000	20	482000	p28	0.63	-74	300	311923
p1	1.00	900	35	522954	p29	0.10	-164	300	129004
p2	1.00	2550	96	522954	p30	0.00	-154	6000	130000
p3	0.99	2550	35	522954	p31	0.00	-158	4700	129004
p4	1.00	2550	35	513538	p32	0.83	-87	300	129004
p5	0.00	2550	35	9416	p33	0.18	-94	300	182919
p6	1.00	4700	75	513538	p34	0.18	-66	300	201615
p7	0.67	4700	35	513538	p35	0.23	-28	300	9416
p8	1.00	4700	35	311923	p36	1.00	95	900	522954
p9	0.00	4700	35	201615	p37	0.10	-165	101	130000
p10	0.00	2550	-1	9416	p38	1.00	-165	101	14289
p11	0.88	300	-35	522954	LNG	0.00	-165	101	115711
p12	1.00	6000	-5	130000	NG-in	1.00	13	6000	130000

Table 2. Stream components

	Components (%)							
Stream name	i-Butane	i-Pentane	Ethylene	Nitrogen	n-Butane	Propane	Ethane	Methane
NG-1	0.3	0.1	0	4	0.5	2.1	5.5	87.5
M4	0	14.7	34	14.7	0	17.6	0	19
NG-in	0.3	0.1	0	4	0.5	2.1	5.5	87.5
P-15	0	0	0	5.7	7.7	25.8	33.4	27.4
P-5	0	0	0	0.4	31.3	42.4	21.2	4.7
P-8	0	0	0	7.9	3.6	19.2	34	35.3
P-9	0	0	0	1.4	15.2	38.9	32.5	12

Process simulation

ASPEN HYSYS 9.0 was used to simulate the cycles and component properties. Code for genetic algorithm (GA) was developed in MATLAB R2018b and linked to ASPEN HYSYS to optimize key parameters. PR-EoS is suitable for the liquefaction of natural gas, especially processes with mixed refrigerant systems. Morosuk et al. (Morosuk, Tesch, Hiemann, Tsatsaronis, & Omar, 2015) and Mehrpoya et al. (Mehrpooya, Sadaghiani, & Hedayat, 2020) used the PR-EoS method to simulate LNG production processes. In this research, Peng-Robinson equations of state (PR-EoS) predict single and mixed components systems' properties.

To validate the used PR-EoS method, the LNG production cycle model from reference (Marmolejo-Correa & Gundersen, 2012) was simulated and examined. Shown in Fig. 3 is the comparison of simulation results by using PR-EoS with reference (Marmolejo-Correa & Gundersen, 2012). Good agreement between results confirms the PR-EoS method used in this research.

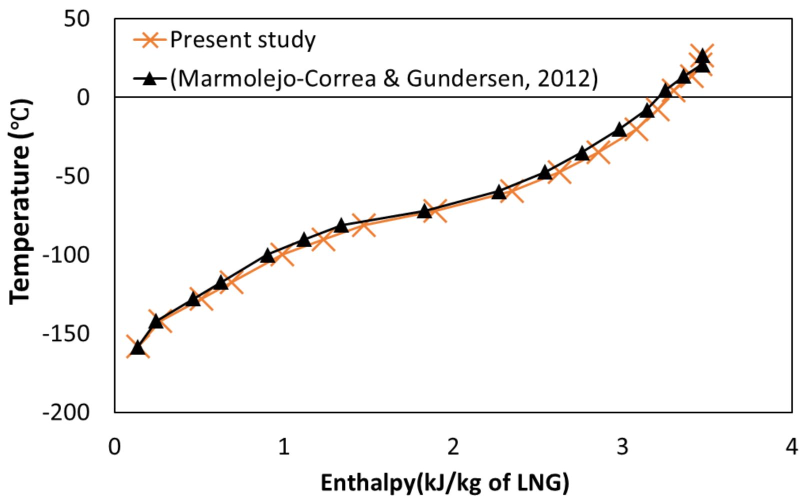


Fig. 3. Validation of the PR-EoS method in the present study.

The constraints and simplifications in both PRICO and LIMUM3 cycle in this study are considered as follows:

- Pressure drop and heat loss are zero in heat exchangers(Marmolejo-Correa & Gundersen, 2012)
- No temperature cross happens in heat exchangers(Marmolejo-Correa & Gundersen, 2012)
- The minimum temperature approach in heat exchangers is in the range of 1℃ -3℃ (Thome, 2010),
- In compressors, the isentropic efficiency is 0.85, and the inlet stream has no liquid phase (Mehrpooya et al., 2020).

Energy analysis

In energy analysis, the energy consumption of liquefaction processes is studied, such as SEC, coefficient of performance (COP), and figure of merit (FOM). SEC is defined as the ratio of energy consumed in process devices (compressors, pumps, and expanders) per one kilogram of LNG. SEC in LNG production processes calculated by Equation 1 as follows(Cardella, Decker, & Klein, 2018; Rehman et al., 2020):

$$SEC = \frac{P_{net}}{\dot{m}_l} \quad (1)$$

Where P_{net} is the total energy consumption in the cycle, and $\dot{m}_l$ is the mass flow rate of LNG. In natural gas liquefaction systems, COP is obtained as follows(Ghorbani, Ebrahimi, Moradi, & Ziabasharhagh, 2020; Tan, Shan, Nie, & Zhao, 2018):

$$COP = \frac{Q_c}{P_{net}} \quad (2)$$

Q_c is the total cold duty in heat exchangers. The higher the value COP, the more the heat is taken from the hot gas streams in heat exchangers for the same amount of power consumption, resulting in higher cycle efficiency. FOM is calculated using Equation 3 as follows(Moran, Shapiro, Boettner, & Bailey, 2010; Rehman et al., 2020):

$$FOM = \frac{W_{rev}}{W_{ac}} \quad (3)$$

Where subscripts "*rev*" and "*ac*" are for the reversible and actual work, respectively.

Exergy analysis

Exergy analysis is performed for the cycles. Exergy of streams and exergy destruction in devices are obtained as follows(Fratzscher, 1997):

$$e = e_c + e_p \quad (4)$$

$$e_p = h - h_0 - T(S - S_0) \quad (5)$$

$$Ex_i + Ex_{Qi} = Ex_o + Ex_{Qo} + W_{sh} + I \quad (6)$$

Where subscripts"i" and"o" stand for the inlet and outlet streams, respectively. Ex_{Qo} is heat transfer exergy, W_{sh} is input power in the device, and I is the exergy destruction, whereas subscripts"c" and "p" mean chemical and physical exergy, respectively. Exergy efficiency can be calculated for the devices and the whole cycle. Table 3 shows the exergy destruction and exergy efficiency equations for all devices (Ghorbani, Mehrpooya, Aasadnia, & Niasar, 2019).

Table 3. Exergy efficiency and exergy destruction equations of devices(Ghorbani, Ebrahimi, Rooholamini, & Ziabasharhagh, 2020; Ghorbani et al., 2019).

Components	Exergy destruction	Exergy efficiency
Compressor and turbine expander	$I = Ex_i - Ex_o + W_{c,e}$	$\frac{Ex_i - Ex_o}{W_{c,e}}$
Heat exchanger	$I = Ex_i - Ex_o$	$\frac{Ex_o}{Ex_{in}}$
Pump	$I = Ex_i - Ex_o + W_p$	$\frac{Ex_i - Ex_o}{W_p}$
Mixer and separator	$I = Ex_i - Ex_o$	$\frac{Ex_0}{Ex_{in}}$
Expansion valve	$I = Ex_i - Ex_o$	$\frac{Ex_0}{Ex_i}$
Cycle	$I_{total} = \sum_i I_i$	$1 - \frac{I_{total}}{P_{net}}$

Economy analysis

An economic analysis is performed to compare the PRICO and LIMUM3 cycles. The CAPEX, OPEX, and O&M expenditures are calculated as annual costs to examine the proposed cycle's economic aspect. In this research, the total CAPITAL cost of liquefaction units is calculated as follows:

$$C_{CAPEX,t} = C_{eq}(1 + C_{ins} + C_{pip} + C_{bld} + C_{elc} + C_{stf} + C_{isu} + C_{eng} + C_{cnt} + C_{ctg} + C_{wrc}) \quad (7)$$

$$C_{eq} = (1 + C_{del})(C_{Hex} + C_{com} + C_{oth}) \quad (8)$$

Table 4 shows the cost factors used in equations 7 and 8(J. Couper, Hartz, & Smith, 2008).

Table 4. Cost factors of CAPEX expenditure

Cost factor	Name	Cost factor	Name
C_{eq}	Equipment expenses	C_{isu}	Cost of insulation
C_{ins}	Installation expenses	C_{ctg}	Unforeseen expenses
C_{pip}	Piping expenses	C_{wrc}	System testing expenses
C_{bld}	Building construction expenses	C_{del}	Delivery expenses
C_{elc}	Electric systems expenses	C_{Hex}	Cost of heat exchangers
C_{stf}	Safety systems expenses	C_{com}	Cost of compressors
C_{eng}	Cost of design and supervision	C_{oth}	Cost of other devices
C_{cnt}	Contracting expenses		

The manufacturing cost of heat exchangers expenses in an LNG production unit is based on the heat transfer surface area (A_{Hex}) and calculated as follows(Khorrammanesh, Amidpour, & Nasr, 2007):

$$C_{hex} = c_{p,hex}.(30000 + 1900(A_{Hex})^{0.83}) \quad (9)$$

The cost of heat exchangers is also related to the working pressure, so the pressure cost factor estimates heat exchanger expenditure more accurately. The pressure cost factor in heat exchanger is calculated by equation 10 and Table 5 (J. R. Couper, Penney, Fair, & Walas, 2005):

$$c_{p,hex} = \alpha + \beta \ln A_{Hex} \quad (10)$$

The cost of a compressor is calculated as follows (J. R. Couper et al., 2005; Ghorbani, Ebrahimi, & Ziabasharhagh, 2020):

$$C_{com} = 7900(H)^{0.62} \quad (11)$$

Where H is the work of the compressor. The amount of annual LNG is calculated as follows(Serio et al., 2015):

$$\dot{m}_{LNG,a} = Y_a.17280000.\dot{m}_{LNG} \quad (12)$$

Table 5. Pressure cost factors in heat exchangers(J. R. Couper et al., 2005)

Working pressure in the heat exchanger (bar)	β	α
1-21	0.05	0.78
21-41	0.07	1.03
41-62	0.12	1.14
61-100	0.15	1.37

Where $Y_a = 0.95$ is the annual rate of cycle activity and $\dot{m}_{LNG}$ is the mass flow rate of LNG (Serio et al., 2015). In equation 12, 200 working days are considered for the peak-shaving. The annual cost of CAPEX, which is related to the value of annual interest rate (z) and payment period (t), is given as follows (J. Couper et al., 2008):

$$C_{CAPEX,a} = C_{CAPEX,t}.\frac{z.(1+z)^t}{(1+z)^t - 1} \quad (13)$$

OPEX expenditures include the cost of power consumption, the natural feed gas cost ($C_{feed,a}$), and charging refrigerants ($C_{feedf,a}$) due to gas leakage in cold boxes and pipes. Annual OPEX and O&M expenses are calculated as follows:

$$C_{OPEX,a} = c_{el}.\dot{m}_{LH_2,a}.SEC + C_{feed,a} + C_{feedf,a} \quad (14)$$

$$C_{O\&M,a} = c_{O\&M}.C_{CAPEX,a} \quad (15)$$

Where c_{el} is the cost of electricity for one kWh, $c_{O\&M}$ the cost factor of operating and maintenance expenditure ($c_{O\&M}$) is assumed from 0.03 to 0.12 for simple and complex cycles, respectively(J. R. Couper, Hertz, & Smith, 2008).

Genetic algorithm

GA method is based on iteration and genetic theory. The GA method is used to optimize the variables: pressure, mass flow rate, temperature, and percentage of mixed refrigerant components in this study. MATLAB R2018b software in conjunction with ASPEN HYSYS 9.0 has been used for this purpose. Table 6 shows the variables and their range of variation.

Table 6. Range of parameters variation in this study.

PRICO				LIMUM3			
Variable	Lower bound	Lower bound	Optimized case	Variable	Lower bound	Lower bound	Optimized case
Mole fraction of Nitrogen in M3 stream	0.100	0.175	0.147	Mole fraction of Nitrogen in p15 stream	0.025	0.065	0.057
Mole fraction of Methane in M3 stream	0.175	0.225	0.19	Mole fraction of Methane in p15 stream	0.250	0.300	0.274
Mole fraction of Ethylene in M3 stream	0.325	0.390	0.340	Mole fraction of Ethane in p15 stream	0.300	0.350	0.334
Mole fraction of Propane in M3 stream	0.175	0.220	0.176	Mole fraction of Propane in p15 stream	0.225	0.270	0.258
Mole fraction of i-Pentane in M3 stream	0.090	0.150	0.147	Mole fraction of n-Butane in p15 stream	0.030	0.080	0.077
The mass flow rate of M3 ($10^5\ ^{kg}/_{h}$)	4.8	5.3	4.82	The mass flow rate of P15 ($10^5\ ^{kg}/_{h}$)	5.15	5.25	5.23
Low pressure of mixed refrigerator cycle (kPa)	250	350	255	Low pressure of mixed refrigerator cycle(kPa)	250	350	300
The temperature of M11(℃)	17	28	20				
The pressure ratio of ComM1 unit	3.3	6	4.01				

In PRICO and LIMUM3 cycles, the percentage of mixed refrigerant composition components is considered an independent parameter in genetic optimization. In the PRICO cycle, the mixed refrigerant mass flow rate, the minimum pressure of the mixed refrigerant, the compression ratio in the compressor (COMM1), and the mixed refrigerant temperature of stream M11 are also considered as independent variables. In the LIMUM3 cycle, the minimum pressure and mixed refrigerant mass flow rate are independent variables. The range of changes of all independent variables is shown in Table 6.

Table 7 shows the properties of the GA used in this study. The objective function is $SEC = \frac{P_{net}}{\dot{m}_l}$, shown in Table 7. The minimum value of the objective function is the best choice in genetic algorithm optimization in this study. Less SEC value means less power consumption to produce one kilogram LNG. Fig. 4 shows the framework and how the GA works in this research. Constraints listed in the section "process description" of this study are considered GA constraints.

Table 7. GA parameters in this study.

Parameters	Value
Objective function	$SEC = \frac{P_{net}}{\dot{m}_l}$
Number of iterations	50
Numbers of population	80
Crossover fraction	0.3

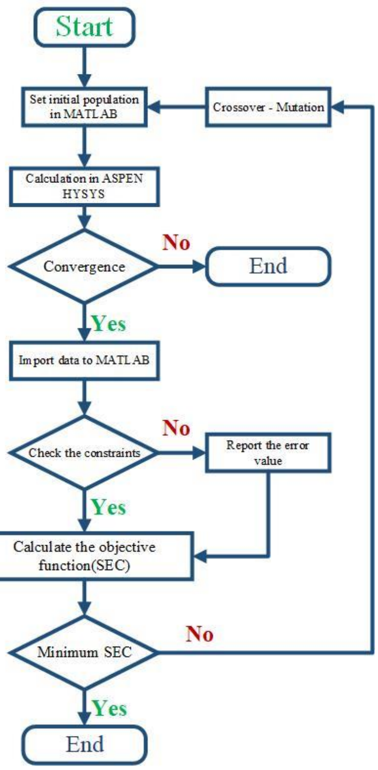


Fig. 4. The framework of the GA method in this study.

The selection of initial values and the range of their changes is the most important part of the GA method in process optimization. If the inappropriate initial values and irrelevant range of variation are selected, the non-convergent solution will result in many iterations(Mirjalili, 2019). By identifying independent and non-independent variables in the simulation, the appropriate initial values for GA optimization are determined. The objective function is considered to be SEC, which is optimized by minimizing it and observing the constraints. After optimization by genetic algorithm, the two cycles of PRICO and

LIMUM3 are compared. The method used to perform the GA optimization is based on He and Lin(He & Lin, 2020) and Yin and Ju research (Yin & Ju, 2020), which has been modified by changing the variables and selecting the appropriate objective function for this research.

Results and discussion

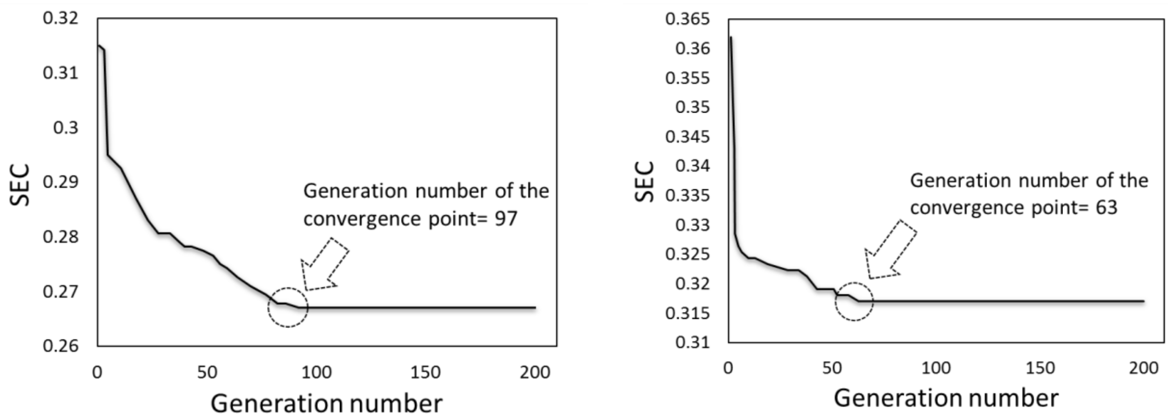
Process optimization

Energy analysis is performed to find the best cycle for the fuel peak-shaving of the Shahid Rajaee power plant. The results of the energy analysis of PRICO and LIMUM3 cycles are given in Table 8. Optimized and base cases are compared in Table 8.

Table 8. Energy analysis results in the base and optimized cases for PRICO and LIMUM3.

	PRICO cycle			LIMUM3 cycle		
Efficiency parameters	Base case	Optimized case	Improvement	Base case	Optimized case	Improvement
FOM	0.53	0.70	+32%	0.229	0.379	+65%
SEC (kWh/kg_{LNG})	0.315	0.267	+15.2%	0.362	0.317	+12.3%
COP	2.563	2.826	+10.2%	2.28	2.488	+9%

According to Table 8, it is crystal clear that PRICO has a better performance than the LIMUM3 cycle due to the lower SEC value. The LIMUM3 cycle has an SEC of 0.317 kWh/kg_{LNG}, which is higher than the PRICO cycle with 0.267 kWh/kg_{LNG}. FOM values of PRICO and LIMUM3 cycles were 0.53 and 0.379, respectively. A lower SEC will also reduce the cost of electricity consumed annually, which will be examined in the economic analysis section. The PRICO cycle has a COP value of 2.826 compared to 2.488 in LIMUM3. According to the energy analysis results in optimized cases, the higher COP and FOM values of the PRICO cycle compared to the LIMUM3 cycle indicate that PRICO has better performance than LIMUM3. Shown in Fig. 5 are the GA optimization convergence diagrams for PRICO and LIMUM3 cycles.



(a) (b)

Fig. 5. The convergence diagram of the GA optimization: (a) PRICO cycle, (b) LIMUM3 cycle.

Table 9. Comparison of previous literature studies(Lee, Long, & Lee, 2012; Won & Kim, 2017) and this study.

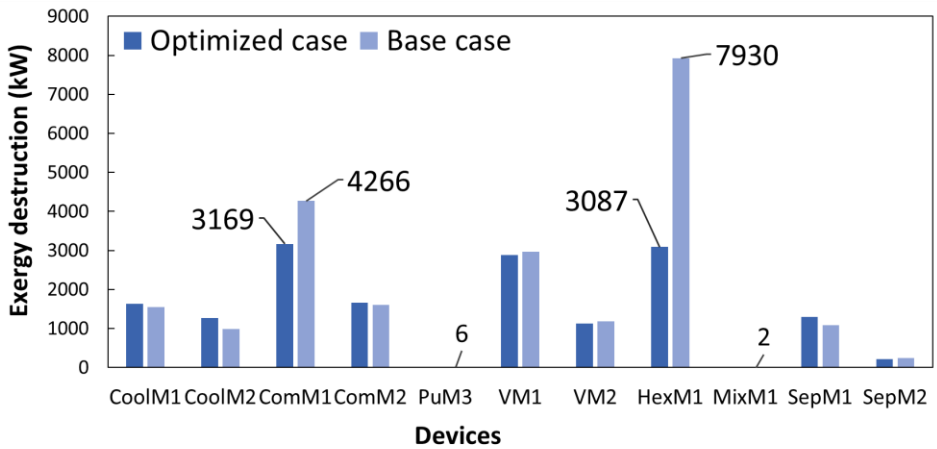
	SEC (kWh/kg_{LNG})	Power consumption (kW)	Capacity of LNG production cycle (kg_{LNG}/h)
This study (Optimized case of PRICO cycle)	0.267	31779	119023
)Lee et al., 2012(	0.311	36698	118000
)Won & Kim, 2017(	0.293	34837	118900

In Fig. 5, it is clear that the curves decrease sharply at the beginning because GA can find the better next generation easier. The optimal generation number of PRICO and LIMUM3 are 97 and 63, respectively. Table 9 compares previous literature studies and the optimized case of the PRICO cycle in this study.

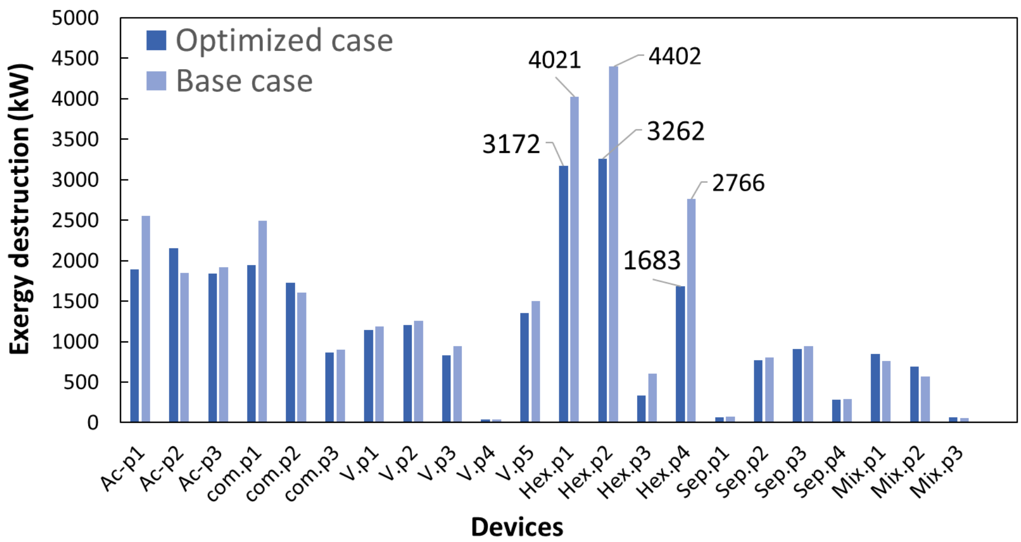
Table 9 compares the performance of the proposed cycle with other similar ones in the literature. SEC of the proposed cycle is 14% less than that in Lee et al. (Lee et al., 2012), which is 10% less than that in reference (Won & Kim, 2017). The lower the specific energy consumption of the cycle, the better the performance cycle. The proposed cycle capacity and power consumption are 119023 kg_{LNG}/h and 31779 MW, respectively.

Exergy analysis

Fig. 6(a) shows the exergy destruction of the PRICO cycle in the base and optimized cases. By comparing the amount of exergy destruction of all devices and identifying devices with high exergy destruction, the cycle's efficiency can be increased by optimizing and reducing exergy destruction. In Fig. 6(b), the comparison of the base case and optimized case in exergy destruction of the LIMUM3 cycle is shown.



(a)



(b)

Fig. 6. Exergy destruction comparison of the base case and optimized cases: (a) PRICO, (b) LIMUM3.

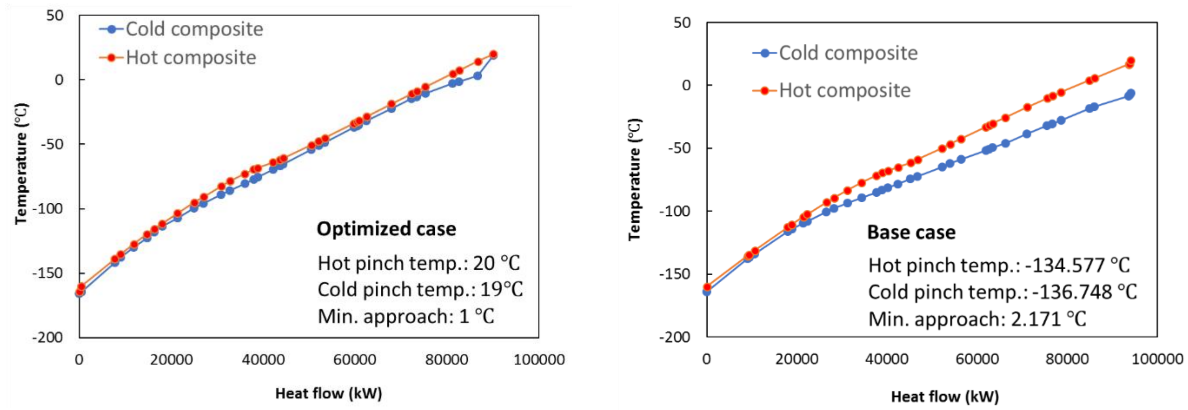
As with Fig. 6(a), it is clear that in the PRICO liquefaction cycle, the HexM1 heat exchanger has the greatest exergy destruction among other devices, which has been reduced in the optimized case by using GA optimization. By changing various parameters in the devices that had a lot of exergy degradation, such as heat exchangers, their efficiency increased. Although some devices will have more exergy destruction after optimization, the cycle's total exergy destruction decreased significantly in the optimized case. There is a great drop in the exergy destruction of Hex.M1 in the PRICO cycle from 7930 kW to 3087 kW. The optimization reduces 5465 kW exergy destruction in the PRICO cycle, 25% less than the base case. The positive effect of optimization is the overall performance-enhancing of the cycle. The exergy efficiency of ComM1 is the same in both base and optimized cases, but due to the reduction of the input mass flow, the amount of exergy destruction is reduced from 4266 kW to 3169 kW in this device. As with Fig. 6(b), three heat exchangers, including Hexp1, Hexp2, and Hexp4, have the highest influences on the total amount of exergy destruction in the LIMUM3 cycle. Optimized cases lead to a 4439 kW reduction in exergy destruction for LIMUM3. The maximum and minimum proportion of exergy destruction in the optimized

LIMUM3 cycle goes to Hex.p2 and V.P4 with 3262kW and 38 kW, respectively. Exergy destruction of the Hex.p2 optimized case decreased 114 kW in comparison with its base case.

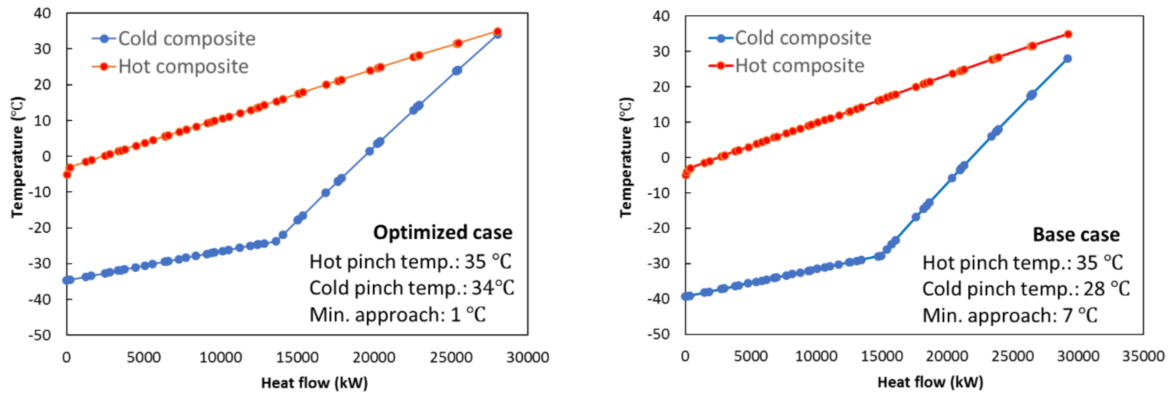
Exergy efficiency in all heat exchangers increased in both the PRICO and LIMUM3 cycles after optimization. Since exergy destruction in MixM1 and SepM2 is not much, high exergy efficiency in such devices does not cause significant enhancement in the cycle's exergy efficiency. The HexM1 heat exchanger of the PRICO cycle had a 0.93 exergy efficiency in the base case and saw a noticeable rise in the optimized case, reaching 0.97. Although the exergy efficiency of ComM1 remained unchanged at 0.82 after optimization, this device experienced a noticeable decrease in exergy destruction due to the mass flow rate drop of mixed refrigerant in the optimized case compared with the base case. In the LIMUM3 cycle, the Sep.P1 and HEX.P3 had the highest exergy efficiency among other devices. Hex.P1, Hex.P2, and Hex.P4 witnessed a modest rise in exergy efficiency in optimized cases. The optimized case of Hex.P4 saw an increase in exergy efficiency, hitting 0.98. The exergy efficiency of the PRICO cycle for the base and the optimized case is 0.43 and 0.52, respectively. This improvement indicates + 20% higher performance in the optimized PRICO cycle. The optimized LIMUM3 cycle's exergy efficiency is 0.35, which has a rise of 0.15 compared to the base cycle.

According to Fig. 6, the Heat exchangers have been identified as the most important devices that significantly influence the whole cycle's efficiency. Consequently, reducing the exergy destruction in heat exchangers can be done in many ways, closing the cold and hot composite curves and adjusting the minimum temperature approach in a suitable range. A low value of minimum temperature approach reduces the amount of exergy destruction, but it requires more heat transfer surface area in a heat exchanger, resulting in higher CAPEX expenditures. In the base cycle, the minimum temperature approach is considered between 1℃- 8℃, but in the optimized cycle, it reduces to the range of 1-2 ℃, which is in good agreement with the study of Thome's research(Thome, 2010).

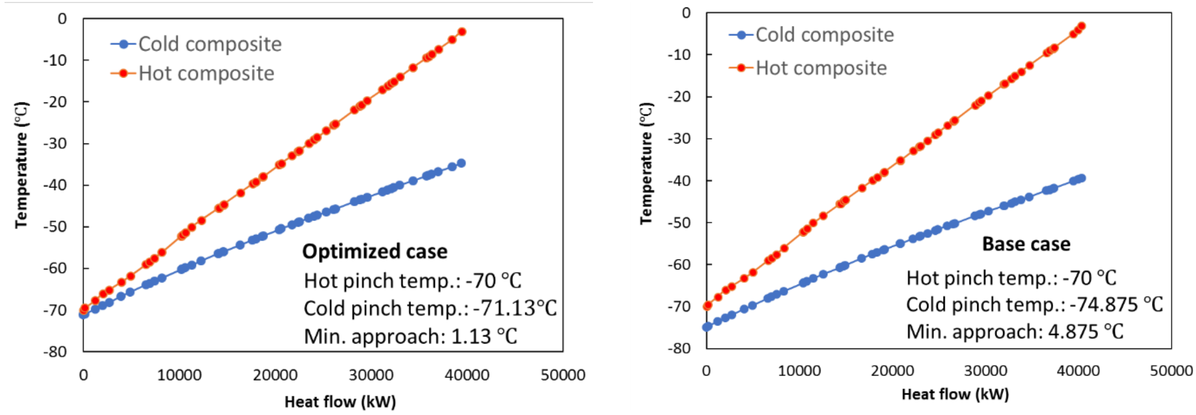
Fig. 7 shows the heat exchangers' hot and cold composite curves in the optimized and base cases. The smaller the area between the two diagrams, the less exergy destruction in the heat exchangers accrues, leading to higher exergy efficiency in the heat exchangers and whole cycle.



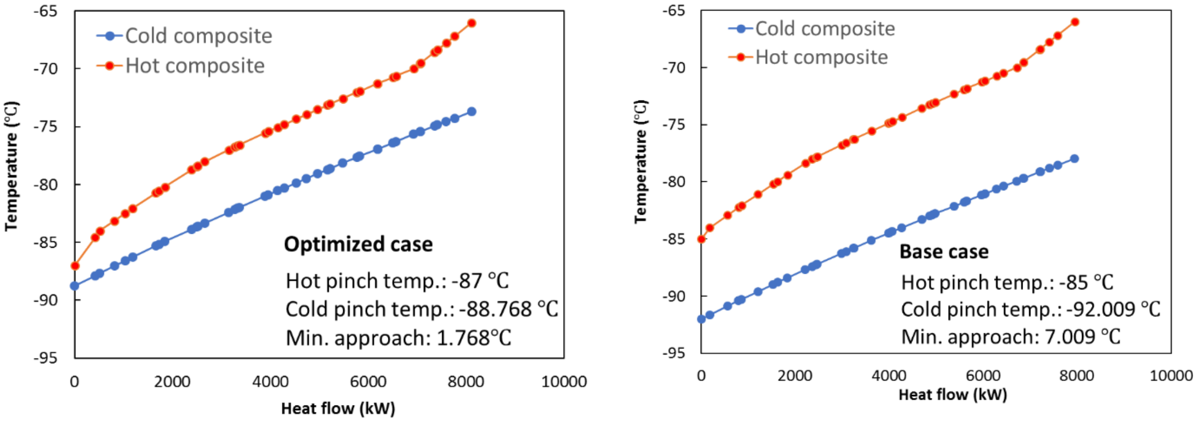
(a) HexM1(PRICO)



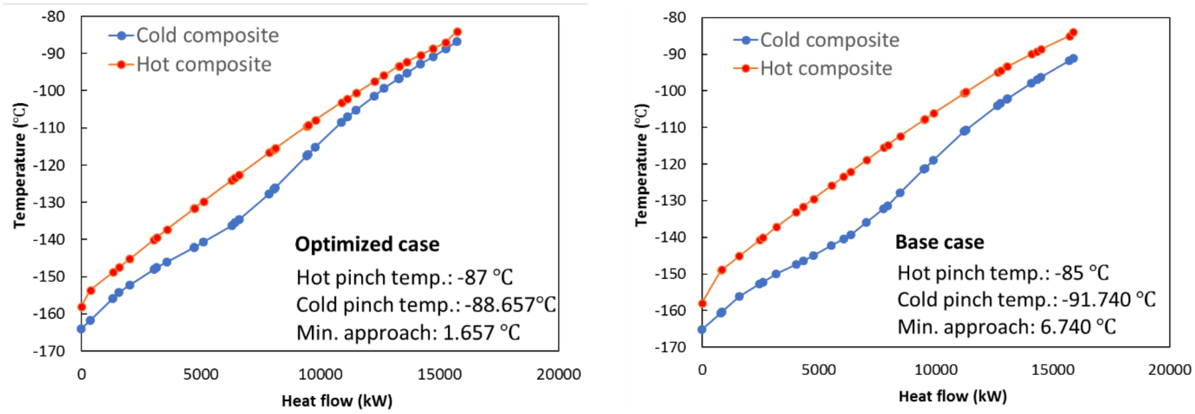
(b) Hex.P1(LIMUM3)



(c) Hex.P2(LIMUM3)



(d) Hex.P3(LIMUM3)



(e) Hex.P4(LIMUM3)

Fig. 7. Composite curves of heat exchangers for the base and the optimized cases: (a) HexM1, (b) Hex.P1, (c) Hex.P2, (d) Hex.P3, (e) Hex.P4.

Fig. 7(a) shows the composite curves of HexM1 in the PRICO cycle; the optimized cases' curves are closer than base cases, which is the optimization goal to reduce exergy destruction. Fig. 7(b) to Fig. 7(e) also show the composite curves in four heat exchangers of the LIMUM3 cycle. Minimum temperature approach decreased in all heat exchangers of LIMUM3 cycle in optimized cases. The area between cold and hot composite curves was reduced in four heat exchangers. Minimum temperature approach and hot and cold pinch temperatures are also shown in Fig. 7.

Economy analyses of the two proposed cycles for the power plant peak-shaving

Fig. 8 shows the results of the economic analysis of PRICO and LIMUM3 in equipment cost (C_{eq}), which is the main cost part of CAPEX expenditures.

As with Fig. 8, the greatest proportion of the total equipment cost goes to heat exchangers in the PRICO cycle, accounting for 39.6 M$, which is 25.6 M$ in LIMUM3. The second rank is allocated to compressors in the PRICO cycle, making up 6.5 M$, followed by other devices expenditures at 6.9 M$. In this study, other equipment costs were calculated using Couper's cost estimate method (JR Couper et al., 2005). Shown in Fig. 9 are the annual OPEX expenses for PRICO and LIMUM3 cycles.

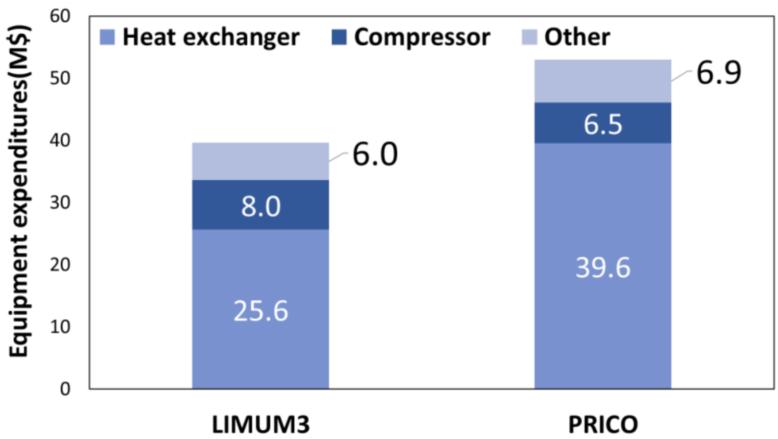


Fig. 8. Comparison of equipment cost of PRICO and LIMUM3 cycles in optimized case.

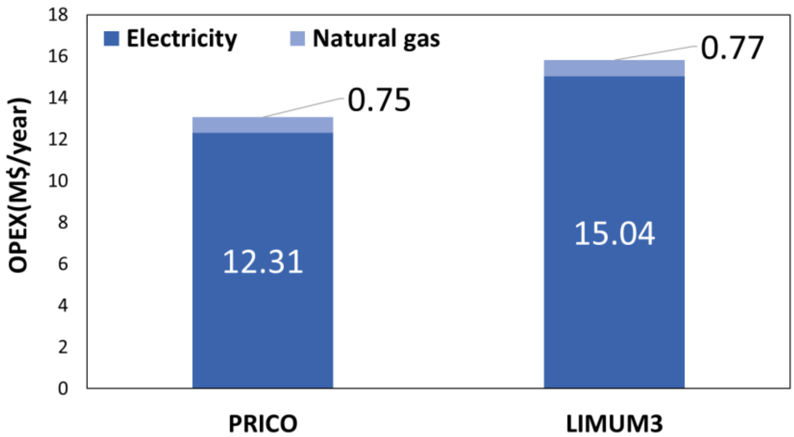


Fig. 9. Comparison of annual OPEX expenses of PRICO and LIMUM3 cycles in optimized case.

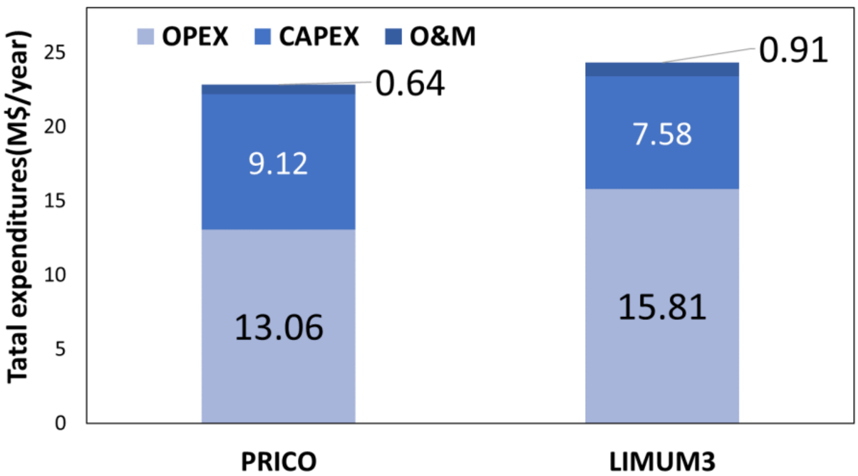


Fig. 10. Comparison of annual CAPEX, OPEX, and O&M expenses for PRICO and LIMUM3 cycles in optimized case.

Fig. 9 shows the annual OPEX cost for two PRICO and LIMUM3 cycles over a year. In the LIMUM3 cycle, the electricity expenses are 15.04 M$, followed by natural gas feed at 0.77 M$. However, by the PRICO cycle, this trend remained unchanged. The first rank goes to electricity, accounting for 12.31 M$. Of the electricity in PRICO and LIMUM3, the latter is of the greater proportion of total expenses. Shown in Fig.

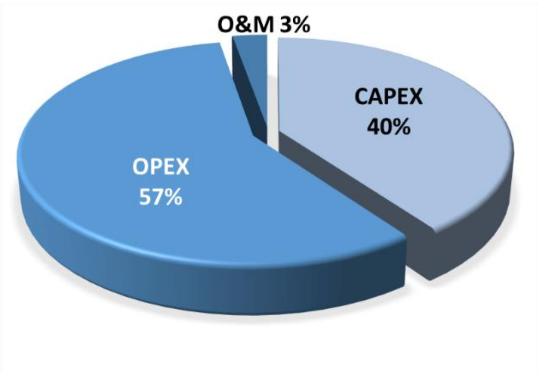
10 are the total expenses for PRICO and LIMUM3 cycle.

Fig. 10 shows the total annual cost, including CAPEX, OPEX, and O&M for the two cycles. OPEX represents the highest cost in LIMUM3 and PRICO cycles. As with the PRICO cycle, it is seen that CAPEX cost has the third rank, at 9.12 M$, which is 7.58M$ in LIMUM3. The lowest proportion of total expenditure goes to O&M not only in PRICO but also in LIMUM3. The data suggest that PRICO is more suitable in economic aspects for the peak-shaving of Shahid Rajaee power plant because the total cost of PRICO is lower than the LIMUM3 cycle.

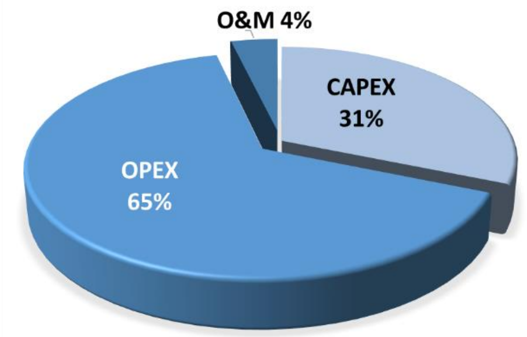
Net present value (NPV) is the value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present. The proposed PRICO cycle has the CAPEX expenditure of 119 M$, which is considered the cash outflow in time zero. The discount rate is 7%. The calculation of annual profit is based on OPEX and O&M expenditures during the lifetime of the proposed cycle. The NPV of the proposed cycle is 213 M$. NPV is calculated as follows:

$$NPV = \sum_{j=1}^{n} \frac{Cash\ flow_j}{(1+r)^j} - Initial\ investment \qquad (16)$$

Where n and j are the number of periods and the cash flow period, respectively, and r is the discount rate. The internal rate of return (IRR) function uses the arguments including Values and Guess. Values are in an array that represents the series of cash flows. Cash flows include investment and net income values over the lifetime of the cycle. CAPEX is assumed as investment expenditure. The discount rate equals IRR When NPV=0. In this study, the guess value is assumed to be 0.15, the IRR value of the final proposed PRICO cycle is 17%. In Fig. 11, two pie charts represent the comparison of different types of costs in PRICO and LIMUM3 cycles.



(a)



(b)

Fig. 11. The proportion of different expenditures: (a) PRICO, (b) LIMUM3.

Two pie charts in Fig. 11 compare three types of annual expenditure for PRICO and LIMUM3 in percentage terms. In the PRICO cycle, OPEX expenditure is the highest cost, amounting to 54%, or over half of all expenses. The next largest sector is CAPEX cost, accounting for 41%. The remaining cost is O&M (5%). As Fig. 11(b), the percentage of OPEX is 65% in LIMUM3, followed by CAPEX at 31%.

According to energy and exergy analyses, the PRICO cycle outperforms LIMUM3. Moreover, the economic analysis shows that the PRICO cycle is more cost-effective than LIMUM3 in total annual cost. Consequently, the PRICO cycle has been identified more appropriately for the Shahid Rajaee power plant's peak-shaving. This is based on some definite reasons, the most important of which is that the PRICO cycle has a lower SEC value than LIMUM3, resulting in lower electricity consumption and lower OPEX expenditures.

Conclusion

Increasing natural gas consumption in cold seasons has caused a lack of fuel for power plants in some areas. Using alternative fuels like diesel and fuel oil causes economic and environmental problems. Fuel peak-shaving in power plants is a suitable solution, storing natural gas fuel in liquid form and consuming it in the cold season. According to the results, the PRICO cycle is proposed to peak-shave the fuel of the Shahid Rajaee power plant, which is the solution to the lack of fuel in the cold seasons. Consequently, by using the proposed cycle, there is no need to use alternatives with environmental problems, leading to cleaner energy production and sustainable energy. Natural gas consumption changes in different seasons during the year. By peak-shaving, the fuel of the power plant, sustainable energy production in a power plant can be accessible in the real world, which is done in this research. The problem of high investment cost is one of the major obstacles to peak-shave the fuel of power plants. This issue could be solved by considering the export of LNG for the peak-shaving system, making it economically viable.

PRICO and LIMUM3 were modified for the natural gas fuel peak-shaving of Shahid Rajaee power plant in Qazvin. Two hundred days were considered hot days for liquefaction and LNG storage and sixty days as peak days for consumption. These two cycles were optimized using a genetic algorithm. Considering the SEC as the objective function, the percentage of refrigerant components and the minimum pressure, temperature, and pressure were optimized at several points in the cycles. By performing the optimization, the SEC of the PRICO cycle was reduced by 15.2% in the optimized case, and in the optimized LIMUM3 cycle, the SEC was 0.317 kWh/kg_{LNG}, improved by 12.3% compared to the base case. The FOM values in the optimized case of PRICO and LIMUM3 cycles were 0.70 and 0.379, respectively. The COP in PRICO is 2.82 in the optimized case.

The optimized PRICO cycle has been compared to previous work in the literature and has a better performance by at least +10%. The PRICO has a lower SEC than the LIMUM3 cycle. The PRICO cycle's exergy efficiency is 52%, which is better than the LIMUM3 cycle of 35%. The CAPEX, OPEX, and O&M expenditures have been calculated and compared in the economic analysis section. The economy, energy, and exergy analysis results show that the PRICO cycle has not only lower cost but also has better performance than LIMUM3. Consequently, the PRICO cycle has been identified more appropriately for the Shahid Rajaee power plant's peak-shaving.

Acknowledgments

The authors would like to thank the research and development (R&D) department of the Shahid Rajaee power plant.

Nomenclature

A_{Hex}	Heat transfer surface area in heat exchangers(m^2)
C_{CAPEX}	Capital cost($)
C_{OPEX}	Cost of operation($)
$C_{O\&M}$	Operating and maintenance expenditures($)
C_{com}	Cost of compressors($)
c_{del}	Delivery cost($)
C_{Hex}	Cost of heat exchangers ($)
C_{oth}	Cost of other devices(excluding compressors, t
C_{tur}	Cost of turbines ($)
Ex	Exergy (kW)
e	exergy(kW)
e^{ph}	Physical exergy(kW)
$f_{p,hex}$	The pressure cost factor in heat exchangers
h	Specific enthalpy (kJ/kg)
H	Work of compressor or turbine(kW)
$\dot{m}_{LNG}$	Mass flow rate of LNG ($^{kg}/_{h}$)
P_{net}	Total power consumption in a cycle(kW)
Q_{cv}	Heat transfer (kW)
I	Exergy destruction(kW)
r	Discount rate
s	Specific entropy(kJ/kg°C)
t	Payment period(year)
W	Work(kW)
z	Annual interest rate

Abbreviations

CAPEX	Capital expenditure
COP	Coefficient of performance
EoS	Equation of state
FOM	Figure of merit
IRR	Internal rate of return
LNG	Liquid natural gas
NPV	Net present value
OPEX	Operation expenses
O&M	Operating and maintenance expenditure
PR	Peng Robinson
SEC	Specific energy consumption

Greek letter

α	Pressure cost factor 1
β	Pressure cost factor 2
η	Exergy efficiency

Subscribe

a	Annual
ac	Actual
c	Chemical
i	In
j	Cash flow period
o	Out
p	Physical
rev	Reversible
t	Total

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