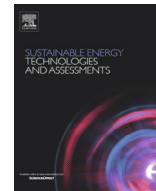




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Original article

Exergoeconomic analysis and multi-objective Pareto optimization of the C3MR liquefaction process



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ABSTRACT

Over the past decades, increasing attention is paid to optimal design and operation of energy intensive industries. A HYSYS simulated model is developed for a propane mixed refrigerant process. Synthesis of pinch and exergy analysis is employed to find the high value of exergetic efficiency. Exergoeconomic analysis also is carried out using the total revenue requirement method. Then a coded genetic algorithm from Matlab software is linked to HYSYS software to optimize the propane mixed refrigerant process. Optimization of the aforementioned system is performed for two singular objective functions. One of the objective functions can minimize the unit cost of exergy, and the other one can maximize exergetic efficiency of the system. In addition, a multi objective function is employed for finding the optimum point in terms of both high exergy efficiency and low total product cost. Results of exergy and exergoeconomic analyses for all the main streams and equipment are presented, and optimization results are compared with corresponding features of the base case design. In the end, sensitivity analysis is employed to examine variation of compressor pressure ratio in terms of total product cost of the system.

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Nomenclature

BL	book life
c	unit exergy cost (\$/kJ)
$\dot{C}$	exergy cost rate (\$/h)
CC	carrying charge
CRF	capital recovery factor
c_w	unit cost of the generated electricity (\$/kW)
e	specific flow exergy (kJ/kgmole)
$\dot{E}$	exergy rate (kW)
Ex	exergy (kW)
f	exergoeconomic factor (%)
FC	fuel cost (\$/s)
I	irreversibility (kW)
i_{eff}	average annual discount rate (cost of money)
j	jth year of operation
m	number of cold streams
$\dot{m}$	flow rate (kg mole/s)
n	number of hot streams
OMC	operating and maintenance cost
PEC	purchase equipment cost (\$)
Q	heat duty (kW)
r	relative cost difference (%)
r_{FC}	annual escalation rate for the fuel cost
ROI	return on investment
r_{OM}	annual escalation rate for the operating and maintenance cost
TCR	total capital recovery
TRR	total revenue requirement
W	work transfer rate (kW)
$\dot{W}$	power (kW)
y	exergy destruction ratio
$\dot{Z}_k$	total cost rate of kth component including Capital investment and operating-maintenance cost
$\dot{Z}_k^{\text{CI}}$	rate of capital investment of kth component
$\dot{Z}_k^{\text{OM}}$	rate of operating and maintenance cost of kth component

Greek letters

τ	annual operating hours (h)
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ε	exergy efficiency
Δ	gradient

Superscripts

CI	capital investment
OM	operating and maintenance
ΔP	pressure component
ΔT	thermal component

Subscripts

0	index for first year of operation
a	air
c	cold
D	destruction
F	fuel
h	hot
i	inlet
k	kth component
L	levelized
o	outlet
P	production
tot	total

Abbreviations

AC	air cooler
APCI	Air Products and Chemicals, Inc
C	compressor
D	flash drum
E	multi stream heat exchanger
LNG	liquefied natural gas
AB	absorption
MIX	mixer
MR	mixed refrigerant
MSF	multi stage flash
NG	natural gas
V	expansion valve

while minimization of requirement energy for compressing is employed as an objective function. Results depicted that the stochastic features of PSP are more beneficial to avoid the local optima and find the more feasible solution. Optimization of shell-and-tube heat exchangers was carried out by Jalilrad [17] using the particle swarm optimization technique. They formulated total cost function based on initial and annual operating costs of the heat exchangers. As a result, the particle swarm optimization selects the parameters for minimizing total cost of the system. Ghorbani et al. [18] proposed a new efficient and robust method through synthesis of ASPEN HYSYS simulator, Genetic Algorithm, and Linear Programming for calculation of HENs. Ghorbani et al. [19] employed particle swarm optimization and non-linear programming techniques to optimize the parameters of mixed refrigerant cycles. They concluded that the particle swarm optimization is superior to the NLP optimization techniques in finding the values of optimizing variables. Amidpour et al. [20] presented a systematic method based on a combination of mathematical methods and thermodynamic viewpoints to acquire optimized design configuration by non-linear programming techniques. They also developed economical optimization and sensitivity analysis in the proposed refrigeration cycles. Shirmohammadi et al. [21] employed a hybrid group method of data handling (GMDH) along

with linking between Aspen HYSYS and MATLAB software, optimized with Genetic algorithm (GA), to obtain efficient polynomial correlation to estimate optimal consumed power for these two cascade cycles.

The purpose of this paper is to examine the exergoeconomic optimization of propane mixed refrigerant (C3MR) processes. Exergy and economic analyses by means of TRR method are herein employed for an exergoeconomic model. Minimizing of the product cost and maximizing the exergetic efficiency as two singular objective functions are carried out using the genetic algorithm. Ultimately, sensitivity analysis was employed to examine variation of compressor pressure ratio in terms of total product cost of the system.

Process description

One of the most prevalent method using in natural gas liquefaction process is the propane pre-cooled phase separator process, also known as the C3MR process [22,23]. Propane can desuperheat the feed stream (natural gas) and condense incompletely the chief refrigerant combination before it goes into the Flash-4. In this process, it can also be evaporated at some pressure levels. Propane

can partly be evaporated in the first three evaporators (HX-1, HX-2, HX-3) and entirely evaporated in the final evaporator (HX-4). The vaporized and liquefied propane at the end of the first heat exchanger (HX-1) are divided in Flash-1. The vapor phase then can be mixed in Mix-3 with the output of Mix-2 and delivered to compressor C-4, while the liquid phase can be expanded in V-1 and fed to the second heat exchanger (HX-2). Having repeated aforementioned process, the propane can completely be evaporated in the fourth heat exchanger (HX-4). The schematic of the process, simulated by HYSYS software, is depicted in Fig. 1.

Exergy analysis

Exergy analysis because of its own certain methods for process evaluation can be confirmed to be an effective method to define the second law efficiency for various processes [24–26]. The main purpose of exergetic analysis is to determine exergetic variables such as exergy efficiency and exergy destruction of the process equipment as well as exergy destruction ratio [18]. Exergy of a stream can be divided into physical and chemical exergy in absence of potential and kinetic energy. Physical and chemical exergy of an ideal mixture can be formulated in Eqs. (1) and (2), respectively:

$$\varepsilon = (h - h_o) - T_o(s - s_o) \quad (1)$$

$$\varepsilon = \sum_{i=1}^n x_i \varepsilon + \sum_{i=1}^n x_i \ln x_i \quad (2)$$

Table 1 depicts calculated variable for C3MR process. These variables, physical and chemical exergy, have been achieved by corresponding values at specific pressure, temperature, vapor fraction, and flow rate according to Table 1.

Composition of the feed gas is shown in Table 2. Additionally, when it comes to exergetic variables, exergy efficiency and destruction of an equipment as well as exergy destruction ratio, are the

most important ones. These variables are formulated by Eqs. (3), (4), and (5), respectively [24]:

$$\varepsilon_k = \frac{\dot{E}_{P,K}}{\dot{E}_{F,K}} = 1 - \frac{(\dot{E}_{D,K} + \dot{E}_{L,K})}{\dot{E}_{F,K}} \quad (3)$$

$$\dot{E}_{D,K} = \dot{E}_{F,K} - \dot{E}_{P,K} - \dot{E}_{L,K} \quad (4)$$

$$y_{D,K} = \frac{\dot{E}_{D,K}}{\dot{E}_{F,tot}} \quad (5)$$

Table 3 presents performance of the compressors and expanders of the integrated process. C5 compressor consumes the highest power among the other devices. It is because of its high pressure ratio and mass flow rate compared to the other compressors.

Table 4 shows the specifications of the heat exchangers in the process. Decreasing the temperature difference between the cold and hot composite curves in the heat exchangers decreases the power consumption of the refrigeration system due to reduction in exergy losses. Number of the heat exchangers sides increases by eliminating the reboiler and condenser in the columns. So by eliminating the reboiler and condenser, capital cost of the columns decreases, and accordingly heat exchangers size and complexity increases.

Table 5 presents amount of consumed power of compressors and the way of calculation of consumed power in the new integrated process.

Table 6 compares new integrated process with the other similar cases. In this process the amount of consumed power is reduced from 0.3677 kWh in terms of one kilogram LNG.

Table 7 respectively show the exergy efficiencies used for calculation of the process equipment cost.

Exergetic variables such as exergy efficiency and destruction have been calculated by values of fuel and product exergy as depicted in Table 8.

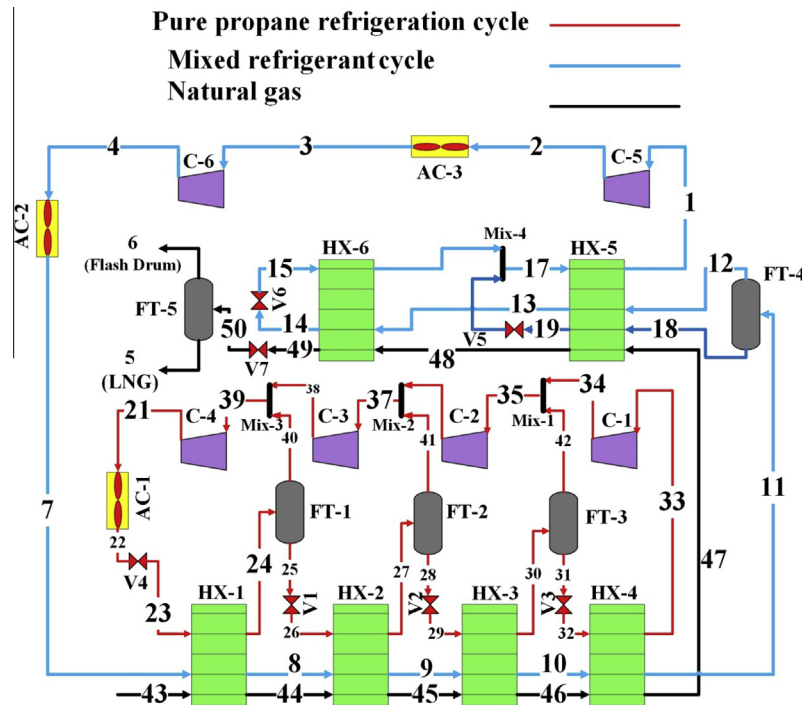


Fig. 1. Schematic of Propane precooled phase separator (C3-MR) process.

Table 1

Calculated variables for selected streams.

Stream	Temperature (K)	Pressure (bar)	Mass Flow (kg/h)	Physical Exergy (kW)	Chemical Exergy (kW)	Total Exergy (kW)
1	230.6	3.0	97.38	3.07	1218.68	1221.76
2	364.5	21.0	97.38	7.58	1218.68	1226.27
3	303.2	21.0	97.38	7.22	1218.68	1225.91
4	368.6	48.6	97.38	9.34	1218.68	1228.03
7	305.0	48.6	97.38	8.88	1218.68	1227.57
8	290.6	48.6	97.38	8.89	1218.68	1227.58
9	278.8	48.6	97.38	8.99	1218.68	1227.68
10	256.8	48.6	97.38	9.35	1218.68	1228.04
11	240.0	48.6	97.38	9.77	1218.68	1228.46
12	240.0	48.6	21.82	2.77	228.74	231.52
13	144.7	48.4	21.82	4.32	228.74	233.07
14	113.0	48.4	21.82	5.02	228.74	233.77
15	106.5	3.0	21.82	4.87	228.74	233.62
16	140.7	3.0	21.82	2.21	228.74	230.96
17	140.2	3.0	97.38	11.61	1218.68	1230.29
18	240.0	48.6	75.56	6.72	990.21	996.93
19	144.8	48.4	75.56	9.51	990.21	999.72
20	139.1	3.0	75.56	9.13	990.21	999.34
21	330.3	14.3	163.035	6.27	2181.10	2187.37
22	313.1	14.3	163.035	5.41	2181.10	2186.51
23	287.6	7.2	163.035	5.20	2181.10	2186.31
24	287.6	7.2	163.035	5.12	2181.10	2186.22
25	287.6	7.2	107.853	3.52	1442.87	1446.39
26	275.6	5.1	107.853	3.49	1442.87	1446.36
27	275.6	5.1	107.853	3.28	1442.87	1446.15
28	275.6	5.1	74.435	2.46	995.80	998.27
29	253.8	2.5	74.435	2.39	995.80	998.20
30	253.8	2.5	74.435	1.68	995.80	997.49
31	253.8	2.5	27.766	0.96	371.46	372.42
32	236.8	1.3	27.766	0.95	371.46	372.41
33	242.0	1.3	27.766	0.17	371.46	371.63
34	268.6	2.5	27.766	0.40	371.46	371.86
35	259.4	2.5	74.435	1.11	995.81	996.9
36	290.1	5.1	74.435	1.80	995.81	997.6
37	285.6	5.1	107.853	2.61	1442.87	1445.49
38	301.4	7.2	107.853	3.12	1442.87	1445.99
39	296.8	7.2	163.035	4.72	2181.1	2185.82
40	287.6	7.2	55.182	1.60	738.23	739.83
41	275.6	5.1	33.417	0.82	447.06	447.88
42	253.8	2.5	46.669	0.71	624.34	625.06
43	300.0	65.0	49.179	7.41	633.21	640.63
44	290.6	65.0	49.179	7.42	633.21	640.63
45	278.8	65.0	49.179	7.44	633.21	640.65
46	256.8	65.0	49.179	7.54	633.21	640.75
47	237.5	65.0	49.179	7.73	633.21	640.94
48	144.7	65.0	49.179	11.29	633.21	644.50
49	113.0	65.0	49.179	13.07	633.21	646.28
50	107.1	1.0	49.179	12.57	633.21	645.79
F. Gas	107.1	1.0	3.835	0.187	25.37	25.56
LNG	107.1	1.0	45.344	12.29	607.93	620.22

Table 2

Properties of feed and product streams and cooling system of process.

Stream	N ₂	CH ₄	C ₂ H ₆	C ₃ H ₈	C ₄ H ₁₀
Feed gas	0.0401	0.8748	0.0550	0.0212	0.0089
24	0	0	0	1	0
12	0.17	0.6554	0.1410	0.0331	0
18	0.0292	0.3217	0.3630	0.2861	0
17	0.07	0.4181	0.2989	0.2131	0
LNG	0.0154	0.8932	0.0591	0.0224	0.0096

Table 3

Compressors performance of the process.

Unit	Pressure ratio	Polytropic Efficiency	Outlet temperature (°C)	Electrical power consumption (kW)
C-1	1.923	80.829	−4.539	0.286185
C-2	2.04	79.954	16.9	0.8797.31
C-3	1.412	78.494	28.27	0.6462
C-4	1.986	79.053	57.19	1.93993
C-5	7	74.471	91.38	6.07064
C-6	2.314	72.183	95.46	2.82035

Table 4
Performance of heat exchangers in new integrated process.

Parameter	Unit					
	HX-1	HX-2	HX-3	HX-4	HX-5	HX-6
Log mean temperature difference (LMTD) [°C]	6.765	7.749	10.61	7.557	7.675	7.790
Heat duty [kW]	7763	9092	14730.44	10755.48	52041.1	6753
Minimum temperature approach [°C]	2.993	3.199	2.991	1.719	3.123	3.123
Number of sides	3	3	3	3	4	3

Table 5
Equipment power consumption and specific power.

		Component name	Power (kW)
Compressors		C-1	0.286185
		C-2	0.879731
		C-3	0.6462
		C-4	1.93993
		C-5	6.07064
		C-6	2.82035
Mass flows (kg/h)	Feed	49.1797	
	LNG	45.34	
	Flash Gas	3.835	
Specific power (kW h/kg LNG)		0.2594	

The exergy efficiency of the precooler and the overall exergy efficiency of the C3-MR process are given by the expression:

$$\begin{aligned} Ex_{pcool} &= ((Ex_{47} - Ex_{43}) + (Ex_{11} - Ex_7)) \\ Ex_{pfeed} &= W_1 + W_2 + W_3 + W_4 \\ \eta_{pcool} &= Ex_{pcool} / Ex_{pfeed} \\ \eta_{pcool} &= 32.06\% \end{aligned} \quad (6)$$

$$\begin{aligned} Ex_{ofeed} &= Ex_{49} - Ex_{43} \\ Ex_{opower} &= W_1 + W_2 + W_3 + W_4 + W_5 + W_6 \\ \eta_{overall} &= Ex_{ofeed} / Ex_{opower} \\ \eta_{overall} &= 44.72\% \end{aligned} \quad (7)$$

The precooler exergetic efficiency and overall exergetic efficiency can be derived from the Eqs. (6) and (7). The exergetic efficiency of precooler is approximately equal to % 33, and the overall exergetic efficiency of process is equal to %44.72.

Exergoeconomic evaluation

Combining the economics principles with the second law of thermodynamics results in exergoeconomic analysis method. In this method, cost value of the exergy for each stream is determined. Based on the cost value of the streams cost of the compo-

Table 6
Comparison between new integrated process and the other processes.

	Refrigeration system	Number of compressors	Number of towers	Specific power (kW-h/kg-LNG)	Comparison
New design	C3MR	6	–	0.2594	–
Mehrpooya et al. design [29]	MFC	4	1	0.364	–
	DMR	3	1	0.375	–
	C3-MR	4	1	0.391	–
	DMR	3	1	0.42	~0.37
Vatani et al. design [30]	C3-MR	–	1	–	–
APCI [31]	Cascade	4	1	–	–
ConocoPhillips design [32]	Cascade	3	2	–	–
ConocoPhillips design [33]	–	5	2 and 1	0.28–0.43, 0.5	~0.35
Ortloff [34]	Pure-MR	–	2–3	–	–
Fluor Technologies alternatives [35]	C3-MR	5	2	0.359	–
Ghorbani et al. design [23]					

Table 7
Exergy efficiencies of the process components.

Component	Exergy efficiencies of the process components
Compressor	$\eta_{ex} = \frac{\sum (\dot{m}e)_i - \sum (\dot{m}e)_o}{W}$
Heat exchanger	$\eta_{ex} = 1 - \left[\frac{\sum (\dot{m}\Delta e)_h}{\sum (\dot{m}\Delta h)_h} \right] - \left[\frac{\sum (\dot{m}\Delta e)_c}{\sum (\dot{m}\Delta h)_c} \right]$
Air Cooler	$\eta_{ex} = \frac{Q \left(1 - \frac{T_0}{T} \right)}{\sum (\dot{m}e)_i - \sum (\dot{m}e)_o}$
Expansion valve	$\eta_{ex} = \frac{e_o^{\Delta T} - e_o^{\Delta P}}{e_i^{\Delta T} - e_o^{\Delta P}}$ $e^{\Delta T} = \int_{T_0}^{T_1} \frac{T - T_0}{T} dh, e^{PH} = e^{\Delta T} + e^{\Delta P}$

nents inefficiencies can be calculated and discussed. Total Revenue Requirement (TRR) method is used in this study for economic analysis [27].

Table 9 respectively show the Purchase cost used for calculation of the process equipment cost.

The levelized annual total revenue requirement (TRR_L) is calculated as follows with the aid of Capital Recovery Factor [28]:

$$TRR_L = CRF \sum_{j=1}^{BL} \frac{TRR_j}{(1 + i_{eff})^j} \quad (8)$$

CRF is calculated according to the following equation:

$$\begin{aligned} CRF &= \frac{i_{eff}(1 + i_{eff})^{BL}}{(1 + i_{eff})^{BL} - 1} \quad n = 30 \text{ years, } i = 0.1, \\ CRF &= 0.1061 \end{aligned} \quad (9)$$

TRR_j is sum of four annual terms including return on investment (ROI), total capital recovery (TCR), operation and maintenance costs (OMC) and fuel costs (FC) as it is mentioned in [28].

$$TRR_j = TCR_j + ROI_j + FC_j + OMC_j \quad (10)$$

Cost of electricity during jth year is calculated as follows:

$$FC_j = FC_0(1 + r_{FC})^j \quad (11)$$

FC₀ is fuel cost at the starting point year. It is calculated as below:

Table 8

Results of the exergetic variable at the component-level.

Equipment	Exergy fuel (kW)	Exergy product (kW)	Exergy destruction (kW)	Efficiency (%)
HX-1	0.079	0.0165	0.062	0.9710
HX-2	0.206	0.1186	0.088	0.9651
HX-3	0.715	0.4617	0.253	0.9381
HX-4	0.773	0.6058	0.167	0.9440
HX-5	8.533	7.9019	0.631	0.9563
HX-6	2.660	2.479	0.180	0.9037
AC-1	1.136	0.857	0.278	75.47
AC-2	0.48	0.462	0.0171	96.45
AC-3	0.397	0.364	0.033	91.59
C-1	0.286	0.222	0.064	77.60
C-2	0.879	0.688	0.191	78.22
C-3	0.646	0.504	0.141	78.14
C-4	1.939	1.552	0.387	80.01
C-5	6.071	4.512	1.558	74.33
C-6	2.820	2.123	0.696	75.29
V1	1446.39	1446.36	0.034	72.31
V2	998.27	998.206	0.064	68.12
V3	372.427	372.413	0.0149	51.2
V4	2186.517	2186.30	0.208	47.9
V5	999.726	999.34	0.379	72.15
V6	233.774	233.62	0.151	69.12
V7	646.287	645.791	0.496	76.12

Table 9

Purchase cost of the process components.

Component	Purchased equipment cost functions
Compressor	$C_C = 7.90(\text{HP})^{0.62}$ C_C = Cost of Compressor (k\$)
Heat exchanger	$C_E = a(V)^b + c$ C_E = Cost of Heat exchanger (\$)
Drum	$C_D = f_m C_b + C_a$ C_D = Cost of Drum (\$) $C_b = 1.218 \exp[9.1 - 0.2889(\ln W) + 0.04576(\ln W)^2]$, 5000 < W < 226000 lb shell weight $C_a = 300D^{0.7396} L^{0.7066}$, 6 < D < 10, 12 < L < 20 ft f_m = Material Factor
Air Cooler	$C_C = 1.218k(1 + fd + fp)Q^{0.86}$, 20 < Q < 200 M BTU/h C_C = Cost of cooler (\$) f_m = Design Type f_p = Design Pressure (psi) a = 0.4692, b = 0.1203, c = 0.0931

$$FC_0 = c_w \times \dot{W} \times \tau \quad (12)$$

where

 τ = total annual time (in hours) that is 7300 h year⁻¹ c_w = unit cost of fuel (0.071 \$ kW h⁻¹) $\dot{W}$ = power (kW)

The levelized annual operating and maintenance costs OMC_L are calculated as follows:

$$OMC_L = OMC_0 \times CELF = OMC_0 \frac{k_{OMC}(1 - k_{OMC}^{BL})}{(1 - k_{OMC})} CRF \quad (13)$$

where

$$k_{OMC} = \frac{1 + r_{OMC}}{1 + i_{iff}} \quad r_{OMC} = \text{constant} \quad (14)$$

r_{OMC} is the annual escalation rate for the operating and maintenance costs. The levelized carrying charges CC_L is calculated as follows:

$$CC_L = TRR_L - FC_L - OMC_L \quad (15)$$

Based on the components purchased cost, capital investment $\dot{Z}_k^{CI}$ and operating and maintenance costs $\dot{Z}_k^{OM}$ of the total plant are gained.

$$\dot{Z}_k^{CI} = \frac{CC_L}{\tau} \frac{PEC_k}{\sum_k PEC_k} \quad (16)$$

$$\dot{Z}_k^{OM} = \frac{OMC_L}{\tau} \frac{PEC_k}{\sum_k PEC_k} \quad (17)$$

where τ and PEC_k are the total annual hours of plant operation and the purchased-equipment cost of the k th component, respectively. $\dot{Z}_k$ is the cost rate associated with the capital investment and operating and maintenance costs:

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} = \frac{CC_L + OMC_L}{\tau} \frac{PEC_k}{\sum_k PEC_k} \quad (18)$$

Rate of levelized costs is computed according to the following equation:

$$\dot{C}_F = \frac{FC_L}{\tau} \quad (19)$$

The annual carrying charges and O&M costs of the system with respect to the contribution of each equipment to the purchased-equipment cost are depicted in Table 10.

Cost balance equations for each equipment are defined based on decision variables and constraints.

The below equation presents relationship between product and total costs of the system:

$$\sum_{j=1}^n \dot{C}_{j,k,in} + \dot{Z}_k^{CI} + \dot{Z}_k^{OM} = \sum_{j=1}^m \dot{C}_{j,k,out} \quad (20)$$

Following these explanations, cost flow rates associated with the total exergy was calculated and presented in Table 11.

Exergoeconomic variables

The main factors of cost in an equipment is defined as capital investment cost $\dot{Z}_k^{CI}$, cost of exergy destruction $\dot{C}_{D,K}$, operation and maintenance cost $\dot{Z}_k^{OM}$ and exergy lost $\dot{C}_{L,K}$ in that equipment.

Table 10

Capital investment and operation and maintenance cost for each equipment.

Equipment	PEC (\$)	$Z(CI)(\$)$	$Z(OMC)(\$)$	$Z(\$)$
HX-1	10786	1.1320	0.0256	1.1576
HX-2	10893	1.1320	0.0256	1.1576
HX-3	10784	1.1323	0.0256	1.1579
HX-4	10884	1.1324	0.0256	1.1580
HX-5	10894	1.1431	0.0258	1.1689
HX-6	10643	1.1324	0.0256	1.1580
C-1	41.946	0.0044	0.0001	0.0045
C-2	125.15	0.0131	0.0003	0.0134
C-3	76.1	0.0080	0.0002	0.0082
C-4	261.39	0.0274	0.0006	0.0280
C-5	590.3	0.0618	0.0014	0.0632
C-6	200.86	0.0210	0.0005	0.0215
AC-1	116.9	0.0122	0.0003	0.0125
AC-2	233.8	0.0245	0.0006	0.0250
AC-3	233.8	0.0245	0.0006	0.0250
Mix-1	63	0.0066	0.0001	0.0067
Mix-2	63	0.0063	0.0001	0.0064
Mix-3	63	0.0063	0.0001	0.0064
Mix-4	63	0.0063	0.0001	0.0064
FT-1	540.2	0.0570	0.0013	0.0583
FT-2	548.34	0.0570	0.0013	0.0583
FT-3	584.61	0.0570	0.0013	0.0583
FT-4	504.23	0.0570	0.0013	0.0583
FT-5	544.27	0.0570	0.0013	0.0583

Table 11

Cost flow rates (C) associated with the total exergy.

Stream	($\frac{\$}{h}$)	Stream	($\frac{\$}{h}$)
1	64.47	27	279.18
2	64.60	28	192.76
3	64.62	29	192.74
4	64.68	30	192.61
7	64.70	31	71.93
8	64.70	32	71.93
9	64.71	33	71.78
10	64.72	34	71.79
11	64.75	35	192.53
12	12.41	36	192.55
13	12.48	37	279.04
14	12.52	38	279.15
15	12.51	39	421.98
16	12.38	40	142.82
17	64.91	41	86.48
18	52.40	42	120.73
19	52.54	43	0.00
20	52.52	44	1.17
21	422.03	45	2.36
22	422.05	46	3.64
23	422.01	47	4.92
24	421.99	48	6.30
25	279.23	49	7.56
26	279.22	50	7.56
LNG	7.30	Flash Gas	0.31

Capital investment cost as well as exergy destruction cost are the most noticeable among aforementioned factors, and apply to evaluate the exergoeconomic factor. The exergoeconomic factor is formulated in the below equation:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + C_{F,k}(\dot{E}x_{D,k} + \dot{E}x_{L,k})} \quad (21)$$

Exergoeconomic factor deals with relative criteria to assess the economical performance of an equipment, whereas exergoeconomic variables such as $\dot{Z}_k$ and $\dot{C}_{D,k}$ are absolute criteria, by which the importance of an equipment is revealed.

Results of exergoeconomic analysis including amount of exergoeconomic factor for each equipment are obtained and presented in Table 12.

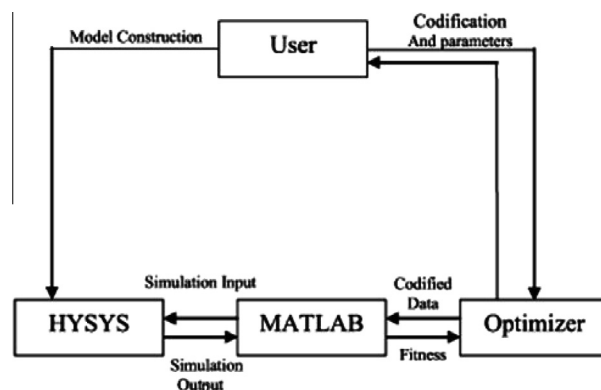
Table 12

Results of the exergoeconomic analyses at the component-level for the reference case.

Equipment	Z ($\frac{\$}{h}$)	C_p ($\frac{\$}{h}$)	C_F ($\frac{\$}{h}$)	$C_D + C_L$ ($\frac{\$}{h}$)	f (%)
HX-1	1.1576	1.1726	0.0150	0.0119	89.92
HX-2	1.1576	1.1968	0.0392	0.0167	89.70
HX-3	1.1579	1.2935	0.1355	0.0480	87.12
HX-4	1.1580	1.3046	0.1466	0.0317	87.92
HX-5	1.1689	1.6044	0.4355	0.0322	70.96
HX-6	1.1580	1.2937	0.1358	0.0092	87.93
C-1	0.0045	0.0076	0.0011	25638	88.39
C-2	0.0134	0.0229	0.0035	76643	85.21
C-3	0.0082	0.1108	0.0026	56493	85.71
C-4	0.0280	0.0490	0.0078	0.0016	80.30
C-5	0.0632	0.1288	0.0243	0.0062	52.57
C-6	0.0215	0.0520	0.0113	0.0028	63.24
Ac-1	0.0125	0	0.0125	0.0031	68.21
Ac-2	0.0250	0	0.0250	88912	88.32
Ac-3	0.0250	0	0.0250	0.0021	86.76
Mix-1	0.0067	192.5306	192.5238	69790	23.01
Mix-2	0.0064	279.0426	279.0362	80825	24.1
Mix-3	0.0064	421.9846	421.9782	0.011	25.01
Mix-4	0.0064	64.9053	64.8989	0.0129	78.01
FT-1	0.0583	422.0499	421.9915	56493	98.01
FT-2	0.0583	279.2378	279.1795	37894	97.12
FT-3	0.0583	192.6657	192.6074	21553	96.11
FT-4	0.0583	64.8045	64.7462	0.0137	33.21
FT-5	0.0583	7.6157	7.5574	0.0013	34.12

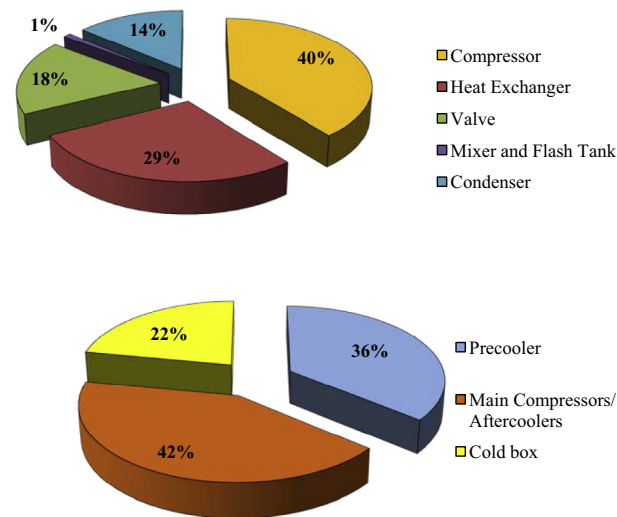
Decision variables, constraints and objective functions

The Propane precooled phase separator (C3-MR) process is simulated by Aspen HYSYS software. Then by linking to Matlab software, exergetic efficiency and total product cost (\$/h) as two objective functions are optimized using Genetic Algorithm depicted in Fig. 2 [19]. In the presented multi objective optimization, there are two objective functions in the optimization process. The first objective function is achieving of maximum exergetic effi-

**Fig. 2.** Schematic of HYSYS software linked by GA optimizer [36].**Table 13**

Considered decision variables.

Decision Variable	Range
T7: entrance temperature to HX-1	305 < T ₇ < 314
T8: entrance temperature to HX-2	290 < T ₈ < 298
T9: entrance temperature to HX-3	278.8 < T ₉ < 305.9
T7: entrance temperature to HX-4	256 < T ₁₀ < 302.8
T7: entrance temperature to Flash 4	240 < T ₁₁ < 249
T48: entrance temperature to HX-5	144.7 < T ₄₈ < 152
T49: exit temperature to HX-5	113 < T ₄₉ < 129
P4: Discharge pressure of compressor C6	30 < P ₄ < 49
Pinch temperature ΔT _{min}	ΔT _{min} ≤ 5 °C

**Fig. 3.** Distribution of exergy destruction in system equipment.

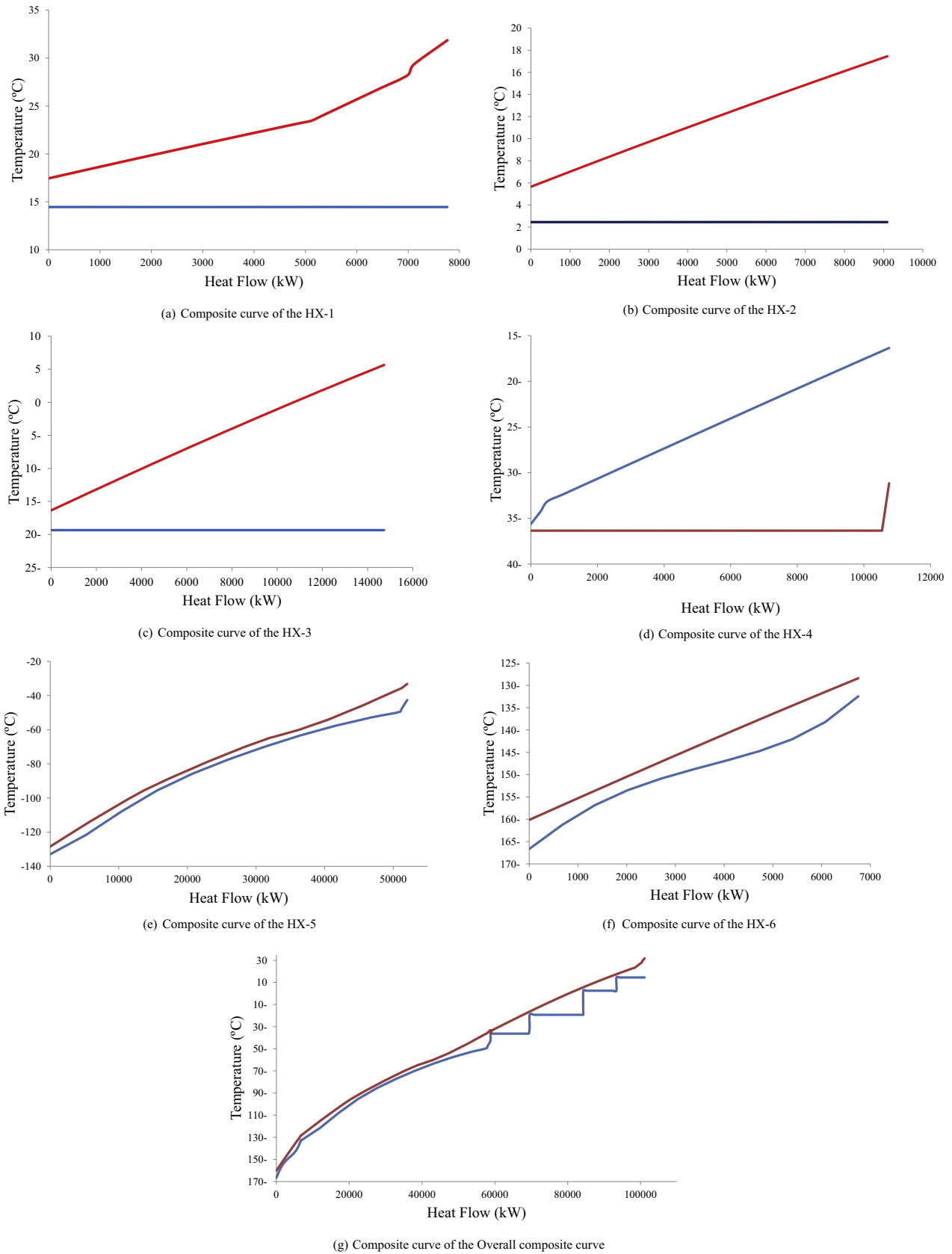


Fig. 4. Composite curve of the heat exchangers (a–f) and Overall composite curve of the process (g).

ciency, and the second one is obtaining of minimum product cost. Present objective functions in a multi objective optimization are usually located on contrary point toward each other. It means that

by increasing one of them, the other one can be decreased and vice versa. Therefore, there is no point that satisfies both function at the same time, and optimization of both functions is impossible simul-

taneously. Thus, Pareto optimized solution is employed in order to obtain appropriate point. In this analysis, Pareto optimized point is selected between maximum exergetic efficiency and minimum product costs. Following constraints and decision variables also are imposed to the model as depicted in Table 13.

Results and discussion

Exergetic and exergoeconomic

Both exergetic efficiency and exergy destruction are calculated for all the equipment by simulating the process and calculating the exergy of the streams. These two values also can be appropriate criteria for evaluating the performance of all the equipment.

According to Fig. 3, after the compressors, which are responsible for 40 percent of the total exergy destruction in this process, there are heat exchangers causing 29 percent of the total exergy destruction. The expansion valves, condenser, and flash tank along with mixers have also noticeable exergy destruction about 19, 14, and 1 percent, respectively.

It also can be concluded that the chief part of the exergy destruction occurs in the compressor 5 (C-5) by analyzing and comparing exergy variable results for the different equipment. This compressor is responsible for more than 1.5 kW of wasted exergy. Among heat exchangers, examined in the process, the HX-5 is responsible for about half of the total exergy destruction among all of the heat exchangers. This heat exchanger has a high exergetic efficiency, which is a proof for its good design. Overall composite curves of the process and composite curves of the heat exchangers are shown in Fig. 4 respectively. Shape of the composite curves shows the quality of thermal design in the process. Bases on the Fig. 4 it can be said that the process thermal design has been done optimally.

The heat exchanger also plays an important role in the entire system. Since fuel and product are huge in amount, any changes which can cause a small improvement in its performance can create great economical benefit.

It should be noted that as the expansion valves have no useful output, their only influence is to reduce the overall output exergy and all of this reduction is actually equal to the amount of the exergy destruction because it associates no useful product.

After completing exergoeconomic analysis of the streams, it is possible to analyse each equipment individually. The exergoeconomic factor i.e., f is a criterion to evaluate the performance of each equipment of the system. These values are calculated and listed in Table 11. The relatively large value of exergoeconomic factor f proposes that the capital investment and O&M costs can be modified. It had better to be checked whether it is economically justified to reduce capital cost of such equipment. Since the capital cost is so high in such equipment, it would not be wrong to come to the conclusion that some equipment lose their economical justification. Decision variable, used in this study, are given in Table 14.

Optimization and sensitivity analysis

Genetic algorithm, which is able to generate a high quality solution, is herein employed to optimize objective functions, decision

variables and constraints. Parameters of Genetic algorithm, used in this study, are given in Table 13. Fig. 5 shows generations in the GA algorithm with respect to optimum exergetic efficiency. Fig. 6 also depicts optimum point in multi objective function.

Additionally, Table 15 compares base case design values with the acquired decision variables values in the optimization procedure. Results reveal that product cost and exergetic efficiency for single objective function are increased and decreased % 6.79 and 0.1968 ($\frac{\$}{h}$) respectively. Furthermore, both exergetic efficiency and product cost are slightly changed in the multi-objective optimization.

Comparison of exergetic parameters between the base case design and the optimized cases design is presented in Table 16. The exergetic efficiency, exergy amount of fuel, exergy lost and destruction for optimal design are % 6.79, 1.6683 kW, 0.2276 kW, 1.2545 kW, smaller than the base case design. Table 16 compares main economic parameters of optimal and base case design. The total fuel and product cost, summation of exergy destruction and exergy lost, and capital investment and operation and maintenance cost in the optimum design are declined in comparison with the base case design. Multi objective optimization results also are presented in Tables 16 and 17, so it is possible to compare to the other cases. Eventually, it can be realized from Fig. 7 that exergetic efficiency in terms of single objective function (Minimize product cost) has the maximum efficiency in comparison with the other cases.

Figs. 8 and 9 indicate the sensitivity analysis for variation of the pressure ratio of compressors 5 and 6 (C5&C6) versus the total product cost. There is direct relationship between the overall product cost of system and compressors' pressure ratio. In other words, increasing the pressure ratio in compressor 6 can lead to increases in the total product cost. The same is true for compressor 5 if the pressure ratio value can be more than 4.5. In contrast, if the pres-

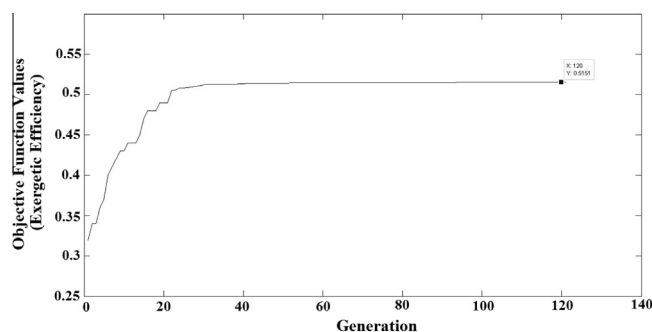


Fig. 5. Schematic of objective function values (exergetic efficiency) with respect to generation.

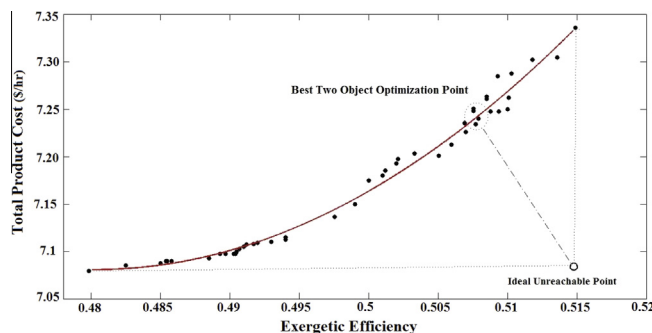


Fig. 6. Schematic of the optimum point in terms of exergetic efficiency and total product cost.

Table 14
Tuning parameters in the Genetic algorithm.

Tuning parameters	Value
Population size	1000
Maximum number of generations	200
Probability of crossover	70%
Probability of mutation	1%
Number of crossover point	2

Table 15

Comparison of decision variables and objective function after exergoeconomic optimization.

Base case design	Single objective (minimum product case)	Single objective (Maximum exergy efficiency)	Multi objective value
$T_7 = 305 \text{ K}$	$T_7 = 309.8862 \text{ K}$	$T_7 = 305.082 \text{ K}$	$T_7 = 305.852 \text{ K}$
$T_8 = 290.6 \text{ K}$	$T_8 = 289.611 \text{ K}$	$T_8 = 289.6155 \text{ K}$	$T_8 = 290.5449 \text{ K}$
$T_9 = 278.8 \text{ K}$	$T_9 = 283.792 \text{ K}$	$T_9 = 278.89 \text{ K}$	$T_9 = 280.0331 \text{ K}$
$T_{10} = 256.8 \text{ K}$	$T_{10} = 261.771 \text{ K}$	$T_{10} = 256.95 \text{ K}$	$T_{10} = 258.4064 \text{ K}$
$T_{11} = 240 \text{ K}$	$T_{11} = 240.4583 \text{ K}$	$T_{11} = 240.402 \text{ K}$	$T_{11} = 244.1029 \text{ K}$
$T_{48} = 144.7 \text{ K}$	$T_{48} = 144.997 \text{ K}$	$T_{48} = 149.66 \text{ K}$	$T_{48} = 146.887 \text{ K}$
$T_{49} = 113 \text{ K}$	$T_{49} = 117.96 \text{ K}$	$T_{49} = 113.021 \text{ K}$	$T_{49} = 113.8518 \text{ K}$
$P_4 = 48.6 \text{ bar}$	$P_4 = 30.144 \text{ bar}$	$P_4 = 30.0039 \text{ bar}$	$P_4 = 30.0190 \text{ bar}$
$Cost_{LNG} = 7.3048 \left(\frac{\$}{h} \right)$	$Cost_{LNG} = 7.1062 \left(\frac{\$}{h} \right)$	$Cost_{LNG} = 7.2835 \left(\frac{\$}{h} \right)$	$Cost_{LNG} = 7.2492 \left(\frac{\$}{h} \right)$
$\eta_{overall} = 44.72\%$	$\eta_{overall} = 47.732\%$	$\eta_{overall} = 51.51\%$	$\eta_{overall} = 50.71\%$

Table 16

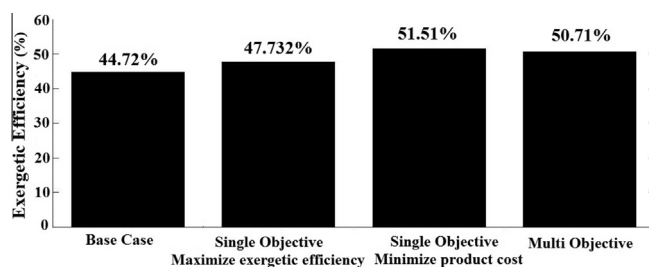
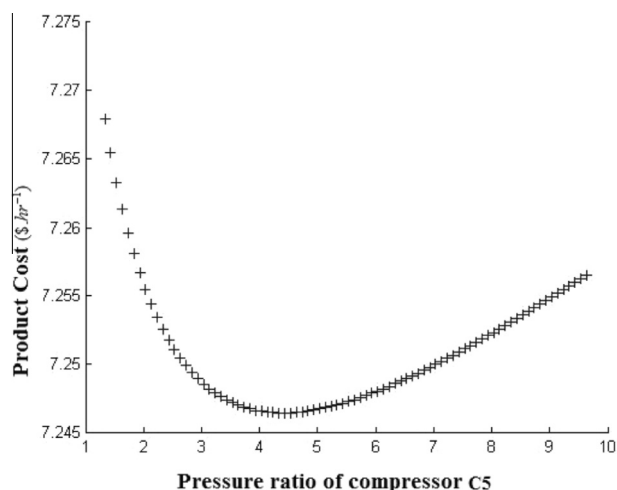
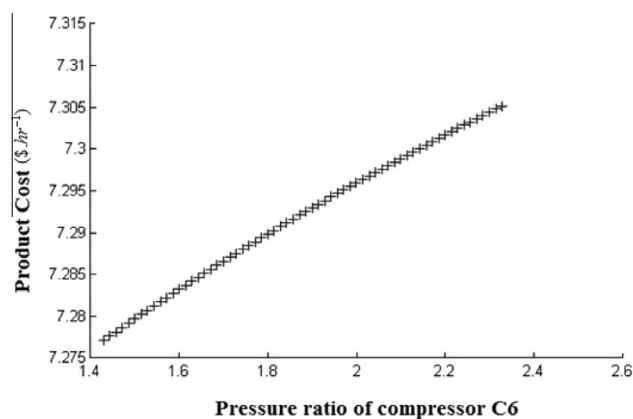
Comparison of exergetic parameters between the base case design and the optimized cases design.

Exergetic parameter	Base case	Single objective (minimum product case)	Single objective (Maximum exergy efficiency)	Multi objective value
$\dot{E}x_{F,total}$	12.6431 KW	11.1656 KW	10.9748 KW	11.0435 KW
$\dot{E}x_{D,total}$	7.4258 KW	6.3427 KW	6.1713 KW	6.7562 KW
$\dot{E}x_{L,total}$	1.3291 KW	1.0996 KW	1.1015 KW	1.1005 KW

Table 17

Comparison of exergoeconomic parameters between the base case design and the optimized cases design.

Exergetic parameter	Base case	Single objective (minimum product case)	Single objective (Maximum exergy efficiency)	Multi objective value
$\dot{C}_{P,total}$	7.3048 $\left(\frac{\$}{h} \right)$	7.1062 $\left(\frac{\$}{h} \right)$	7.2760 $\left(\frac{\$}{h} \right)$	7.2492 $\left(\frac{\$}{h} \right)$
$\dot{C}_{F,total}$	3.1365 $\left(\frac{\$}{h} \right)$	3.1060 $\left(\frac{\$}{h} \right)$	3.1186 $\left(\frac{\$}{h} \right)$	3.0986 $\left(\frac{\$}{h} \right)$
$\dot{C}_{D,total} + \dot{C}_{L,total}$	0.2922 $\left(\frac{\$}{h} \right)$	0.087 $\left(\frac{\$}{h} \right)$	0.04213 $\left(\frac{\$}{h} \right)$	0.04113 $\left(\frac{\$}{h} \right)$
$\dot{Z}_{total}$	7.4770 $\left(\frac{\$}{h} \right)$	7.44598 $\left(\frac{\$}{h} \right)$	7.4637 $\left(\frac{\$}{h} \right)$	7.4624 $\left(\frac{\$}{h} \right)$

**Fig. 7.** Comparison of exergetic efficiency for various cases.**Fig. 8.** Variation of the pressure ratio of compressor 5 with respect to total product cost.**Fig. 9.** Variation of the pressure ratio of compressor 6 with respect to total product cost.

sure ratio equal to a value less than 4.5, it cannot be economically justified.

Conclusion

Optimization of the Propane Mixed Refrigerant (C3MR) process is developed based on a synthesis of pinch and exergy analysis as well as exergoeconomic analysis. Multi-objective optimization is carried out by implementing decision variables and proper constraints using the GA. Both economic and energetic features are improved independently and simultaneously. These features such as overall exergetic efficiency and exergoeconomic parameters

are compared to the base case design. All of the three optimization cases including single-objective function (maximizing exergetic efficiency), single-objective function (minimizing product cost) and multi-objective function are carried out and the above-mentioned parameters are improved significantly. Sensitivity analysis ultimately is employed to examine variation of compressor pressure ratio in terms of total product cost of the system.

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Appendix A. Main and auxiliary equations for the equipment:

Equip.	Main equation	Auxiliary equation
HX-1	$\dot{C}_{43} + \dot{C}_{23} + \dot{C}_7 + \dot{Z}_{HX-1} = \dot{C}_{44} + \dot{C}_{24} + \dot{C}_8$	$\frac{\dot{C}_{24}}{E_{24}} = \frac{\dot{C}_{23}}{E_{23}}, \frac{\dot{C}_{43} - \dot{C}_{44}}{E_{43} - E_{44}} = \frac{\dot{C}_7 - \dot{C}_8}{E_7 - E_8}$
HX-2	$\dot{C}_{44} + \dot{C}_{26} + \dot{C}_8 + \dot{Z}_{HX-2} = \dot{C}_{45} + \dot{C}_{27} + \dot{C}_9$	$\frac{\dot{C}_{26}}{E_{26}} = \frac{\dot{C}_{27}}{E_{27}}, \frac{\dot{C}_{44} - \dot{C}_{45}}{E_{44} - E_{45}} = \frac{\dot{C}_8 - \dot{C}_9}{E_8 - E_9}$
HX-3	$\dot{C}_{45} + \dot{C}_{29} + \dot{C}_9 + \dot{Z}_{HX-3} = \dot{C}_{46} + \dot{C}_{30} + \dot{C}_{10}$	$\frac{\dot{C}_{29}}{E_{29}} = \frac{\dot{C}_{30}}{E_{30}}, \frac{\dot{C}_{45} - \dot{C}_{46}}{E_{45} - E_{46}} = \frac{\dot{C}_9 - \dot{C}_{10}}{E_9 - E_{10}}$
HX-4	$\dot{C}_{46} + \dot{C}_{32} + \dot{C}_{10} + \dot{Z}_{HX-4} = \dot{C}_{47} + \dot{C}_{33} + \dot{C}_{11}$	$\frac{\dot{C}_{32}}{E_{32}} = \frac{\dot{C}_{33}}{E_{33}}, \frac{\dot{C}_{46} - \dot{C}_{47}}{E_{46} - E_{47}} = \frac{\dot{C}_{10} - \dot{C}_{11}}{E_{10} - E_{11}}$
HX-5	$\dot{C}_{47} + \dot{C}_{17} + \dot{C}_{18} + \dot{C}_{12} + \dot{Z}_{HX-5} = \dot{C}_{48} + \dot{C}_1 + \dot{C}_{19} + \dot{C}_{13}$	$\frac{\dot{C}_{17}}{E_{17}} = \frac{\dot{C}_1}{E_1}, \frac{\dot{C}_{48} - \dot{C}_{47}}{E_{48} - E_{47}} = \frac{\dot{C}_{19} - \dot{C}_{18}}{E_{19} - E_{18}} = \frac{\dot{C}_{13} - \dot{C}_{12}}{E_{13} - E_{12}}$
HX-6	$\dot{C}_{48} + \dot{C}_{15} + \dot{C}_{13} + \dot{Z}_{HX-6} = \dot{C}_{49} + \dot{C}_{16} + \dot{C}_{14}$	$\frac{\dot{C}_{15}}{E_{15}} = \frac{\dot{C}_{16}}{E_{16}}, \frac{\dot{C}_{48} - \dot{C}_{49}}{E_{48} - E_{49}} = \frac{\dot{C}_{14} - \dot{C}_{13}}{E_{14} - E_{13}}$
C-1	$\dot{C}_{33} + \dot{C}_{W1} + \dot{Z}_{C-1} = \dot{C}_{34}$	None
C-2	$\dot{C}_{35} + \dot{C}_{W2} + \dot{Z}_{C-2} = \dot{C}_{36}$	None
C-3	$\dot{C}_{37} + \dot{C}_{W3} + \dot{Z}_{C-3} = \dot{C}_{38}$	None
C-4	$\dot{C}_{39} + \dot{C}_{W4} + \dot{Z}_{C-4} = \dot{C}_{21}$	None
C-5	$\dot{C}_1 + \dot{C}_{W5} + \dot{Z}_{C-5} = \dot{C}_2$	None
C-6	$\dot{C}_3 + \dot{C}_{W6} + \dot{Z}_{C-6} = \dot{C}_{40}$	None
AC-1	$\dot{C}_{21} + \dot{Z}_{AC-1} + \dot{C}_{W-AC1} = \dot{C}_{22}$	None
AC-2	$\dot{C}_4 + \dot{Z}_{AC-2} + \dot{C}_{W-AC2} = \dot{C}_7$	None
AC-3	$\dot{C}_2 + \dot{Z}_{AC-3} + \dot{C}_{W-AC3} = \dot{C}_3$	None
FT1	$\dot{C}_{24} + \dot{Z}_{FT1} = \dot{C}_{25} + \dot{C}_{40}$	$\frac{\dot{C}_{25}}{E_{25}} = \frac{\dot{C}_{40}}{E_{40}}$
FT2	$\dot{C}_{27} + \dot{Z}_{FT2} = \dot{C}_{28} + \dot{C}_{41}$	$\frac{\dot{C}_{28}}{E_{28}} = \frac{\dot{C}_{41}}{E_{41}}$
FT3	$\dot{C}_{30} + \dot{Z}_{FT3} = \dot{C}_{31} + \dot{C}_{42}$	$\frac{\dot{C}_{31}}{E_{31}} = \frac{\dot{C}_{42}}{E_{42}}$
FT4	$\dot{C}_{11} + \dot{Z}_{FT4} = \dot{C}_{12} + \dot{C}_{18}$	$\frac{\dot{C}_{12}}{E_{12}} = \frac{\dot{C}_{18}}{E_{18}}$
FT5	$\dot{C}_{50} + \dot{Z}_{FT5} = \dot{C}_{LNG} + \dot{C}_{FG}$	$\frac{\dot{C}_{LNG}}{E_{LNG}} = \frac{\dot{C}_{FG}}{E_{FG}}$
V-1	$\dot{C}_{25} = \dot{C}_{26}$	None
V-2	$\dot{C}_{28} = \dot{C}_{29}$	None
V-3	$\dot{C}_{31} = \dot{C}_{32}$	None
V-4	$\dot{C}_{22} = \dot{C}_{23}$	None
V-5	$\dot{C}_{19} = \dot{C}_{20}$	None
V-6	$\dot{C}_{14} = \dot{C}_{15}$	None
V-7	$\dot{C}_{49} = \dot{C}_{50}$	None
MIX1	$\dot{C}_{34} + \dot{C}_{42} = \dot{C}_{45}$	None
MIX2	$\dot{C}_{41} + \dot{C}_{36} = \dot{C}_{37}$	None
MIX3	$\dot{C}_{38} + \dot{C}_{40} = \dot{C}_{39}$	None
MIX4	$\dot{C}_{20} + \dot{C}_{16} = \dot{C}_{17}$	None

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