

Advanced Exergoeconomic Analysis of C3MR, MFC and DMR Refrigeration Cycles in an Integrated Cryogenic Process

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Abstract: C3MR, MFC, and DMR processes in an integrated LNG-NGL-NRU structure are investigated using the conventional and advanced exergy and exergoeconomic analyses. The results of advanced exergy analysis reveal that in most of the equipment, the highest amount of irreversibility is occurred because of endogenous exergy destruction. In C3MR process, compressor C5 with 9730 kW; in MFC process, compressor C1 with 6342 kW; and in DMR process, compressor C3 with 10008 kW; have the most amount of avoidable endogenous exergy destruction in comparison with the other equipment. According to the advanced exergoeconomic analysis, the amount of endogenous part of exergy destruction cost and investment cost is higher than the exogenous part for most of the equipment, representing that interactions among the equipment is not considerable. Compressors have the highest amount of avoidable endogenous investment cost in all of the processes. Furthermore, in C3MR process, HX2 heat exchanger with 1121 \$/h; in MFC process, compressor C1 with 450 \$/h; and in DMR process, HX3 heat exchanger with 3955 \$/h; have the most amount of avoidable endogenous exergy destruction cost. Based on total costs defined for the equipment, in C3MR process, HX2 heat exchanger with 1126 \$/h should be modified. In MFC process, compressor C1 with 504.7 \$/h should be considered. In DMR process, HX3 heat exchanger with 3963 \$/h should be improved its performance. Finally, sensitivity analysis as well as validation have been conducted, and three different strategies are used to reduce the cost of avoidable exergy destruction of system equipment.

Keywords: Advanced exergy analysis; Advanced exergoeconomic analysis; Exergy destruction cost; Cryogenic process

1. Introduction

Enhancing the energy efficiency of the liquefaction processes can be the most important issue in LNG plants (Mehdizadeh-Fard, Pourfayaz, Mehrpooya, & Kasaeian, 2018). The availability and low cost of natural gas open the possibility of transporting it to places where there is significant demand (Raj, Suman, Ghandehariun, Kumar, & Tiwari, 2016). Natural gas can be transported long distances as liquefied natural gas (LNG) (Raj et al., 2016). Natural gas is a mixture of

paraffinic hydrocarbons such as methane, ethane, propane, butane, *etc.*, and the combustion of natural gas gives off lower emissions of CO₂ and other pollutants than the combustion of coal and oil (Davarpanah, Mirshekari, Behbahani, & Hemati, 2017) (Mazarei, Davarpanah, Ebadati, & Mirshekari, 2018). Thus, natural gas has emerged as a preferred fuel due to its inherent environmental benignity, greater efficiency, and cost effectiveness (Mehrpooya, Jarrahan, & Pishvaie, 2006). Liquefying the natural gas to reduce its volume by a factor of

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approximately 600 for transportation has been identified as a practical solution when the distance between natural gas reservoirs to downstream markets is long enough (Mehrpooya, Sharifzadeh, and Rosen, 2015). Natural gas liquefaction processes are energy-intensive and capital-intensive, so promoting the use of clean natural gas drives efforts to save process energy consumption and optimize the process configurations (Ding, Sun, Sun, & Chen, 2017). The importance of energy saving for high energy demand industries increased in recent years because of economic factors and surging in fuel costs, in order to inspire more and more efficient use of energy (Aslani, Akbari, & Tabasi, 2018). The increasing demand and cost of energy lead to develop more efficient energy consuming methods, especially in complex energy intensive industries (Mehdizadeh Fard, Pourfayaz, Kasaeian, and Mehrpooya, 2017). Several studies have been carried out for obtaining possible improvement of various processes and systems in terms of thermodynamic laws in low temperature applications (Shirmohammadi, Ghorbani, Hamed, Hamed, & Romeo, 2015). Exergy analysis has been employed as a tool for the integration of very complex energy systems (Romeo, Usón, Valero, & Escosa, 2010). As an illustration for conventional exergy and exergoeconomic analyses, the comprehensive analyses of exergy and exergoeconomic are applied to an integrated process of LNG, NGL and NRU with reasonable energy consumption and high ethane recovery (Ghorbani, Hamed, & Amidpour, 2016). Advanced exergy-based methods use the outcomes of the conventional analyses by presenting new calculation steps to disclose equipment interactions and possibility for enhancement (Petrakopoulou, Tsatsaronis, & Morosuk, 2013). Exergy destruction can be divided into endogenous and exogenous parts to increase the interactions among system equipment and offers valuable data for refining an exergy conversion system, chiefly while the concept is united with the concept of avoidable and unavoidable exergy destruction (Kelly, Tsatsaronis, & Morosuk, 2009). A detailed advanced exergetic analysis of a novel co-

generation concept that combines LNG regasification with the generation of electricity is investigated (Tsatsaronis & Morosuk, 2010). An electricity-generating facility operating with natural gas is examined using advanced exergetic and exergoeconomic analyses (Açıkkalp, Aras, & Hepbasli, 2014). Advanced Exergoeconomic evaluation of single mixed refrigerant natural gas liquefaction processes was carried out (Mehrpooya & Ansarinasab, 2015b). Additionally, advanced exergoeconomic analysis was employed for analyzing multistage mixed refrigerant systems (Mehrpooya & Ansarinasab, 2015a). Advanced exergy analysis has been also employed for evaluating of novel flash based Helium recovery from natural gas processes. Results of endogenous and exogenous destructions demonstrates that portion of endogenous exergy destruction among equipment is higher than the exogenous portion and interactions among the equipment do not affect the inefficiencies significantly (Mehrpooya & Shafaei, 2016).

In this paper, C3MR, MFC, and DMR processes in an integrated LNG-NGL-NRU structure are investigated using the conventional and advanced exergy and exergoeconomic analyses. Suggestions to improve the system economical parameters as well as equipment performance along with sensitivity analysis are also provided.

2. Process Description

Process flow diagram of C3MR, MFC and DMR process in the integrated structure of natural gas liquids, natural gas liquefaction, and nitrogen removal unit are presented in Figures 1, 2 and 3, respectively. NGL recovery section, nitrogen rejection unit and LNG production section for these processes are basically the same; consequently, these cases have just been explained for MFC process in the following sections. Table 1 illustrates properties of feed and product streams and refrigeration system for C3MR, MFC and DMR processes. Tables 2, 3 and 4 represent thermodynamic data like temperature, pressure and flow rate of different streams for C3MR, MFC and DMR processes, respectively.

Table 1. Properties of feed, product streams and cooling system of process

Stream	N2	CH4	C2H6	C3H8	C4H10+	CO2	C2H4
C3MR process							
Feed gas	0.0545	0.8251	0.0579	0.036	0.0240	0.002	0
LNG	0.012	0.9822	0.0054	0	0	0	0
NGL	0	0	0.4641	0.314	0.2086	0.0123	0
Nitrogen	0.9966	0.0034	0	0	0	0	0
116	0.0616	0.9324	0.0051	0	0	0.0005	0
200	0	0	0	1	0	0	0
300	0.2566	0.3341	0.2390	0.170	0	0	0
Side1	0	0	0.6407	0.242	0.0912	0.0253	0
Side2	0	0	0.6457	0.181	0.0948	0.0784	0
Side3	0.0001	0.1441	0.4408	0.172	0.0996	0.1425	0
115	0.0081	0.3370	0.1181	0.193	0.3370	0.0030	0
127	0.0175	0.9773	0.0048	0	0	0	0
108	0.0581	0.8623	0.0533	0.024	0	0.0019	0
131	0.0643	0.9355	0.0002	0	0	0	0
MFC process							
Feed gas	0.0545	0.825	0.0579	0.0365	0.024	0.002	0
LNG	0.0088	0.984	0.0063	0.0005	0	0	0
NGL	0	0	0.4636	0.3197	0.212	0.0039	0
Nitrogen	0.9948	0.0005	0	0	0	0	0
200	0	0.136	0.3547	0.2098	0	0	0.2992
300	0.279	0.471	0.1879	0.0618	0	0	0
400	0	0	0.1787	0.6784	0.142	0	0
Side1	0	0	0.6873	0.2356	0.068	0.0087	0
Side2	0	0	0.7488	0.1421	0.069	0.0399	0
Side3	0	0.003	0.5063	0.1384	0.074	0.27	0
115	0.0614	0.930	0.0059	0.0005	0	0.0021	0
129	0.0122	0.981	0.0062	0.0005	0	0	0
118	0.0238	0.971	0.0049	0.0004	0	0	0
DMR process							
Feed gas	0.0545	0.8251	0.0579	0.036	0.024	0.002	0
LNG	0.012	0.9823	0.0052	0.0005	0	0	0
NGL	0	0	0.4636	0.319	0.212	0.003	0
Nitrogen	0.9948	0.0005	0	0	0	0	0
200	0	0	0.2482	0.641	0.1103	0	0
300	0.1284	0.3918	0.2802	0.1996	0	0	0
Side1	0	0.0343	0.3960	0.295	0.259	0.015	0
Side2	0	0.0770	0.3398	0.284	0.286	0.012	0
Side3	0.0004	0.1737	0.3325	0.245	0.235	0.012	0
115	0.0617	0.9322	0.0050	0	0	0.0006	0
133	0.0642	0.9356	0.0002	0	0	0	0
134	0.012	0.9823	0.0052	0.0005	0	0	0

Table 2. Thermodynamic properties of streams for C3MR configuration

Stream	T (°C)	P (kPa)	Molar flow rate (kg mole/h)	Stream	T (°C)	P (kPa)	Molar flow rate (kg mole/h)
Feed gas	37	6309	14000	200	35	1430	25000
101	4	6309	14000	201	1.63	500	25000
102	-17	6309	14000	204	1.63	500	5633
103	-41	6309	14000	206	14.34	500	5633
106	-41	6309	5201	209	-25.4	200	7470
108	-77.1	2600	7802	212	-42.3	100	3516
109	-41	6309	299.1	214	-30.3	100	3194
111	-45.6	2550	697.8	216	-31.4	100	3516
112	-92	6309	5201	217	7.8	250	3516
113	-103	2500	5201	219	15.8	500	13144.8
114	-62	6309	299.1	220	12	500	25000
115	-64.5	2500	299.1	221	63.05	1430	25000
116	-99.8	2500	12390	300	38	3800	37000
117	-114	1379	12390	302	-17	3800	37000
118	-119	1379	12390	304	-28	3800	23799.7
119	-164	1358	10297.8	308	-134	200	13200
120	-164	1358	9680	310	-60.5	200	37000
122	-120	1358	632.4	311	-169	3800	23799.7
126	-170	1358	9680	313	-144	200	23799.7
127	-118	1400	13133.8	314	105	2200	37000
128	-118	1400	13133.8	315	38	2200	37000
130	-118	1400	170.2	Side1	13.98	2500	2700
131	75	1400	170.2	Side2	-6.34	2500	2700
134	-132	1367	1199	Side3	-36.9	2500	2700
135	-118	1400	11764.4	Side1R	35	2500	2700
136	-108	1400	11764.4	Side2R	0	2500	2700
137	-72.9	2500	11764.4	Side3R	-20	2500	2700
138	-126	2500	11764.4	NGL	25.8	2500	1610
139	-165	2500	11764.4	LNG	-164	1000	11764.4
140	-164	1	11764.4	Nitrogen	20	1358	632.4

Table 3. Streams thermodynamic properties for MFC configuration

Stream	T (°C)	P(kPa)	Mass flow(kg/s)	Stream	T(°C)	P (kPa)	Mass flow(kg/s)
Feed gas	37	6309	84.785	203	-85	2790	156.721
101	8	6309	84.785	204	-86.6	600	156.721
103	-27	6309	67.353	206	-27	600	156.721
104	-27	6309	17.431	207	30	1500	156.721
105	-27	6309	33.676	208	35	1500	156.721
106	-27	6309	33.676	209	77.92	2790	156.721
107	-66.3	2600	33.676	300	35	2900	244.120
108	-88	6309	33.676	301	8	2900	244.120
109	-27	6309	5.229	302	-29	2900	244.120
110	-27	6309	12.201	303	-50	2900	244.120
111	-30.4	2550	12.201	304	-173	2900	244.120
112	-50	6309	5.229	305	-177	330	244.120
113	-51.1	2500	5.229	308	35	2500	244.120
114	-102	2500	33.676	309	47.98	2900	244.120
115	-98.9	2500	58.424	400	36	1700	339.077
116	-113	1379	58.424	401	8.8	1700	339.077
117	-119	1379	58.424	402	8.8	1700	169.538
118	-119	1400	68.692	403	-27	1700	169.538
119	-118	1400	68.692	404	-27.8	310	169.538
120	-164	1358	80.341	405	1.83	310	169.538
121	-164	1358	75.521	406	37.38	670	169.538
122	-170	1358	75.521	407	8.8	1700	169.538
123	-118	1400	15.452	408	1.51	700	169.538
124	-118	1400	1.921	409	26.2	700	169.538
125	-75	1400	1.921	410	31	670	339.077
126	-118	1400	13.531	411	78.39	1700	339.077
127	-132	1400	13.531	Side1	14.50	2500	46.338
128	-131	1367	13.531	Side2	6.81	2500	45.455
129	-118	1400	53.416	Side3	-7.4	2500	49.774
130	-99	1400	53.416	Side1R	35	2500	46.338
131	7.20	6300	53.416	Side2R	0	2500	45.455
134	-164	101.3	53.416	Side3R	-20	2500	49.774
200	35	2790	156.721	NGL	27.34	2500	26.381
201	3	2790	156.721	LNG	-164	101.3	52.324
202	-31	2790	156.721	Nitrogen	-30	1358	4.820

Table.4. Streams thermodynamic properties for DMR configuration

Stream	T (°C)	P (kPa)	Molar Flow (kgmole/h)	Stream	T (°C)	P (kPa)	Molar Flow (kgmole/h)
Feed gas	37	6309	14672.508	139	-165	101.3	11627
101	3	6309	14672.508	200	36.8	1900	30000
102	-33	6309	14672.508	201	0	1900	30000
103	-33	6309	12670.271	202	0	1900	13200
104	-33	6309	2002.236	203	-1.2	800	13200
105	-33	6309	5068.108	204	26.3	800	13200
106	-33	6309	7602.163	205	0	1900	16800
107	-33	6309	600.670	206	-33	1900	16800
108	-33	6309	1401.565	207	-34.5	300	16800
109	-71	2600	7602.163	208	-8.75	300	16800
110	-50	6309	600.671	209	-8	300	16800
111	-37.1	2550	1401.565	210	38.39	800	16800
112	-52.32	2500	600.671	211	33.11	800	30000
113	-88	6309	5068.108	212	78.44	1900	30000
114	-102.7	2500	5068.108	300	35	2100	40500
116	-114.3	1379	12356.271	302	-34	2100	40500
117	-119	1379	12356.271	303	-34	2100	14221
118	-118.7	1400	13862.962	304	-128	2100	14221
119	-158	1358	11699.102	305	-129	150	14221
121	-170	1358	10997.156	309	-183.9	150	26278
122	-158	1358	701.946	310	-144	150	26278
123	-120	1358	701.946	311	-137.7	150	40500
124	-40	1358	701.946	312	-64.37	150	40500
125	-5	1358	701.946	313	-64	150	40500
127	-118	1400	13862.9	314	107.5	2100	40500
128	-118	1400	2214.57	Side1	12.97	2500	2700
129	-118	1400	275.271	Side2	-4.88	2500	2700
130	-188	1400	1939.301	Side3	-42.25	2500	2700.03
131	-75	1400	275.271	Side1R	35	2500	2700
134	-118	1400	11627.846	Side2R	0	2500	2700
135	-109	1400	11627.846	Side3R	0	2500	2700
136	-7.94	6300	11627.846	NGL	32.81	2500	2315
137	-134	6300	11627.846	LNG	-165.5	101.3	11627
138	-168	6300	11627.846	Nitrogen	30	1358	701

2.1. NGL Recovery Section

Inlet feed stream is entered into the multi-stream heat exchangers HX1 and HX2 and is cooled up to -27 . The outlet gas from the NGL recovery unit follows into the D3 separator. Line 105 is delivered into the HX3 and is cooled. The stream after passing through V6 sends into the highest tray of NGL tower. Line 106 is delivered into an expander and after dropping its pressure enters into the top side of NGL tower. Pressure of the stream is diminished to the operation pressure of the tower. The liquefied product is separated into two parts. A part of that is delivered to heat exchanger HX3 and after passing through V5 enters into the down side of the column. The outlet streams from the heat exchanger are returned to the column. Stream 115 from by passing through HX4 and expansion valve is finally prepared to send to the nitrogen removal unit (Cuellar, Wilkinson, Hudson, & Pierce, 2002).

2.2. Nitrogen Rejection Unit

The stream 117 at the temperature of -119 °C and pressure of 13.79 bar is entered to nitrogen rejection column. Stream 118 is exited from the bottom of column and after passing through HX3 is entered into the separator D2 in phases of liquid and gas. Line 123 is separated into the two parts. Line 126 is sent to HX4 multi-stream heat exchanger and its temperature drops and converts to liquid. Then, the cooled liquid by passing through an expansion valve V10 is delivered to the top of the nitrogen rejection tower as washing liquid. Line 124, comprising gaseous phase, is also entered into NRU tower by passing through HX3 and supply required heating load of tower.

2.3. LNG Production Section

Liquid gas, line 129, from the bottom of D2 is exited and ready to be sent to liquefaction exchanger after separating of ethane and nitrogen gases and reaches to the standard amount. First, it is heated by passing through the heat exchanger HX4 and converts to gaseous phase, and the gas phase enters to the compressor C3 to increase the pressure up to 63 bar. After that, the temperature and pressure by passing through the heat exchanger HX4 and HX3 reach to -164 and 63

bar. Finally, for converting to the final product it is passed through throttle valve V8 and its pressure is reduced up to atmosphere pressure and entered into the phase separator of D1. The final product i.e. LNG is exited from the bottom of the separator. Gas stream is also

sent out from the top of the separator to the atmosphere.

2.4. Refrigeration Cycles

2.4.1. C3MR process

C3MR process has consisted of two refrigeration cycle, i.e. cycle 200 and 300, used for precooling and liquefaction, respectively. As can be seen in Table 1, this cycle only contains pure propane. This cycle provides the required cold utility in HX1, HX2 and HX3 heat exchangers (Ghorbani, Hamed, & Amidpour, 2016).

2.4.2. MFC process

MFC (Mixed Fluid Cascade) cycle is employed to meet the requirements cooling. This system has three continuous cycles with mixed refrigerant. Cycle 400 is the hottest cycle and utilizes ethane, propane, and n-butane (Ghorbani, Hamed, Amidpour, & Mehrpooya, 2016).

2.4.3. DMR process

In DMR process, cycle 200 for precooling and cycle 300 for liquefaction have been employed to meet the requirements cooling.

3. Methodology

3.1. Conventional Exergy Analysis

Exergy is a tool to measure distance of a system from reference state (Aghniaey & Mahmoudi, 2014). The reference state is also called the dead state, which is in fact the same as surrounding (Ghorbani, Mafi, Amidpour, Nayanian, & Salehi, 2013). The total exergy of multi component streams is the sum of its two contributions: the exergy change due to chemical exergy, and physical exergy (Khademi, Jafarkazemi, Ahmadifard, & Younesnejad, 2013; Shirmohammadi, Soltanieh, & Romeo, 2018):

$$e = e^{ph} + e^{ch} \quad (1)$$

Physical exergy is calculated as follow (Pattanayak, Sahu, & Mohanty, 2017):

$$e^{ph} = h - h_0 - T_0(s - s_0) \quad (2)$$

In which the subscript "0", refers to the ambient temperature and pressure. Irreversibility or exergy destruction can be calculated by difference between the fuel exergy rate and product exergy rate and defined as follow (Abbassi & Aliehyaei, 2004):

$$\dot{E}_D = \dot{E}_F - \dot{E}_P \quad (3)$$

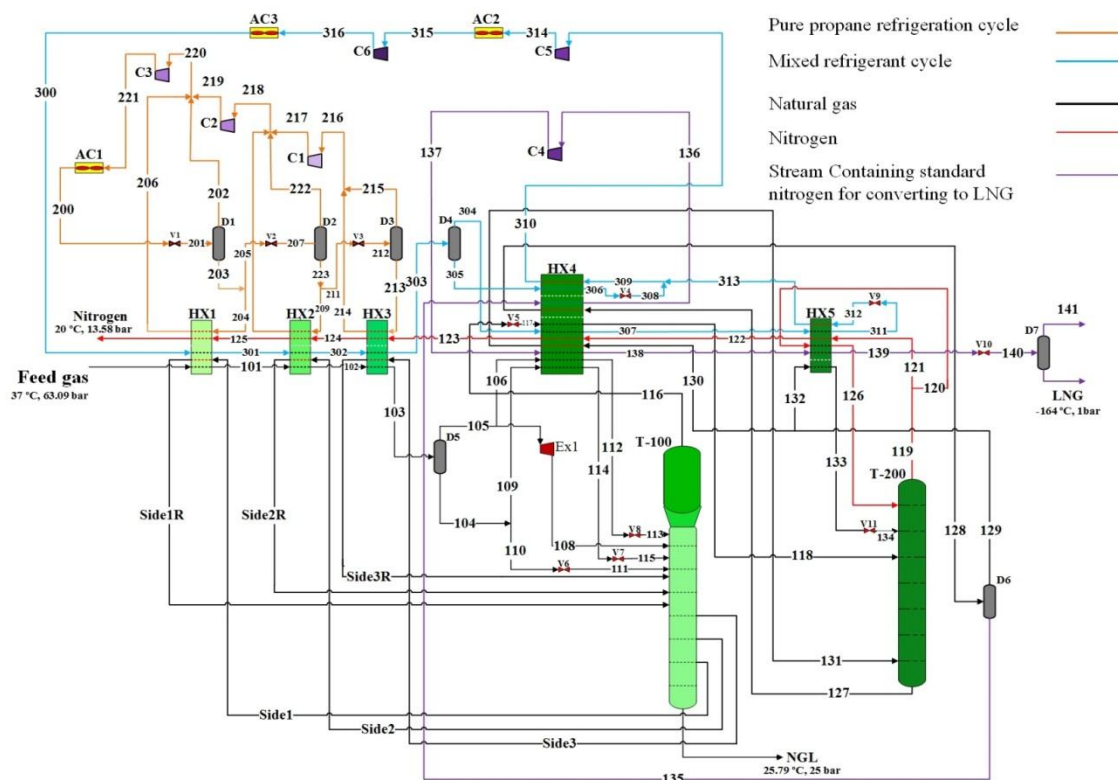


Figure 1. Process flow diagram of the C3MR configuration

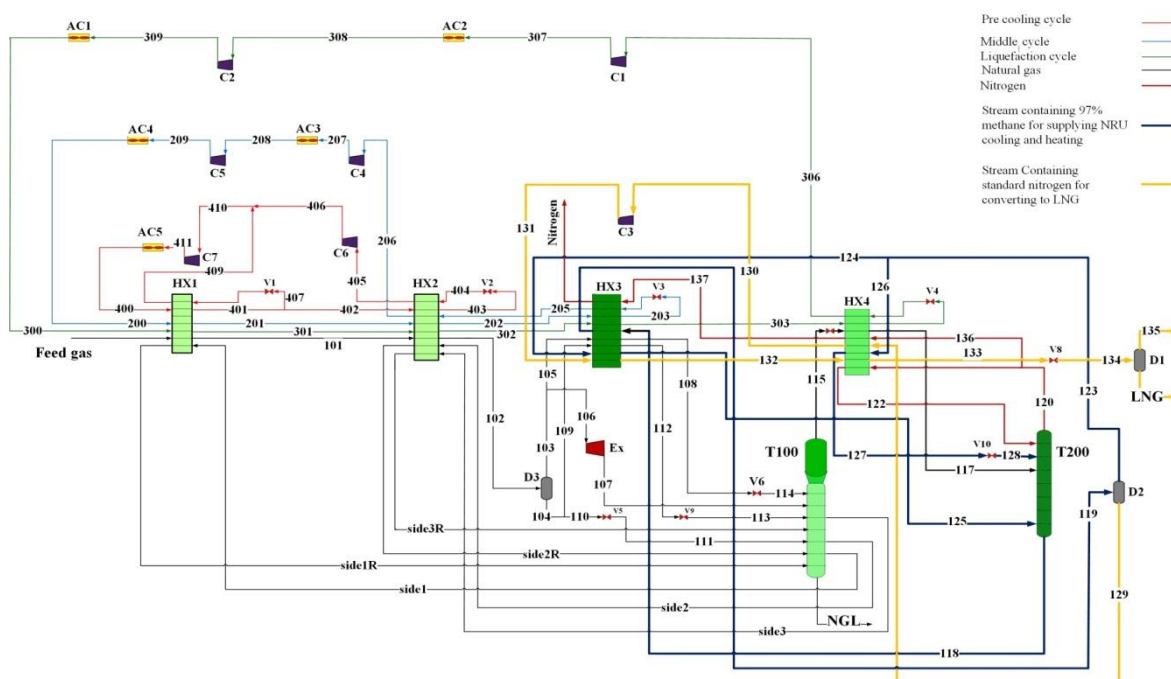


Figure 2. Process flow diagram of the MFC configuration

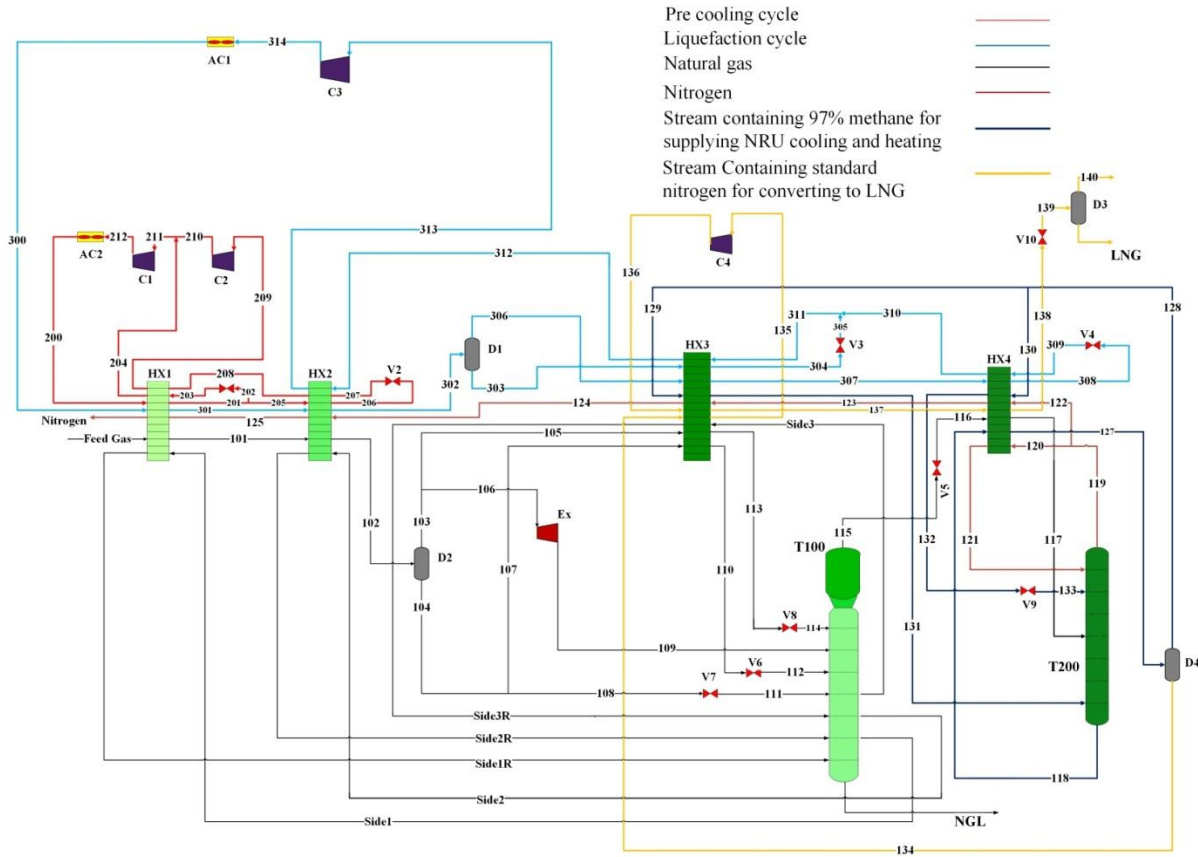


Figure 3. Process flow diagram of the DMR configuration

Exergetic efficiency of each equipment is also calculated as follow (Shariati Niasar et al., 2017):

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = 1 - \frac{\dot{E}_D}{\dot{E}_F} \quad (4)$$

Exergy destruction ratio is another parameter in exergy analysis can be defined as below (Mafi, Ghorbani, Salehi, Amidpour, & Mousavi Nayenian, 2014):

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

3.2. Advanced Exergy Analysis

Exergetic efficiency and exergy destruction, calculating by exergy analysis, and are used to carry out the advanced exergy analysis of the process equipment. The irreversibility of the equipment can be determined by conventional exergy analysis; however, another tool is needed to discrete irreversibility that occurs within the equipment, or the one that depends on the other equipment. Advanced exergetic analysis divides the irreversibility of a device into two points of view i.e. origin of irreversibility and potency to remove or decrease. It also can be separated into two parts Based on the source of the exergy

destruction; endogenous exergy destruction and exogenous exergy destruction. The endogenous part occurs even if other equipment operates ideally, whereas the exogenous part is the result of the other parts not working ideally. Using engineering method, we can calculate the endogenous part of the exergy destruction. In this method, for process equipment, the graph $\dot{E}_{D,total}$ is plotted with respect to $\dot{E}_{D,others}$ such as Fig 4. The y-intercept of this graph for each equipment represents the endogenous exergy destruction of that equipment.

By calculating the endogenous exergy destruction, exogenous exergy destruction can be defined as below (Mehdizadeh-Fard et al., 2018):

$$\dot{E}_{D,k}^{EX} = \dot{E}_{D,k} - \dot{E}_{D,k}^{EN} \quad (6)$$

Based on the potency to remove or decrease, the exergy destruction is separated into two other parts; avoidable exergy destruction and unavoidable exergy destruction. The unavoidable part is limited by technological restriction, while avoidable part can be reduced by improvement of the system. Table 5 presents assumptions for the advanced exergoeconomic analysis for calculating the

unavoidable part (Petrakopoulou, Tsatsaronis, & Morosuk, 2014).

The term $\left(\frac{\dot{E}_D}{\dot{E}_p}\right)_k^{UN}$ is used to calculate unavoidable exergy destruction in kth equipment, which directed from the case where only unavoidable exergy destruction occurs. Thus the unavoidable exergy is calculated by (Mehrpooya, Ansarinassab, Sharifzadeh, & Rosen, 2018):

$$\dot{E}_{D,k}^{UN} = \dot{E}_{p,k} \left(\frac{\dot{E}_D}{\dot{E}_p}\right)_k^{UN} \quad (7)$$

Where $\dot{E}_{p,k}$ is stand for exergy product of each equipment. Now the avoidable part can be calculated from difference of total exergy destruction and unavoidable exergy destruction as below:

$$\dot{E}_{D,k}^{AV} = \dot{E}_{D,k} - \dot{E}_{D,k}^{UN} \quad (8)$$

Where $\dot{E}_{D,k}$ is stand for exergy destruction of each equipment. After splitting the exergy destruction of each equipment into four categories i.e. endogenous, exogenous, avoidable, and unavoidable parts, the task left to be done is to evaluate how different categories of the exergy destruction can be combined and used to provide expressive information. To make applicable results, avoidable and unavoidable exergy will be divided into two more section, endogenous and exogenous parts. Thus total exergy destruction is divided into four parts, namely Avoidable endogenous exergy destruction ($\dot{E}_{D,k}^{AV,EN}$), Avoidable exogenous exergy destruction ($\dot{E}_{D,k}^{AV,EX}$), Unavoidable endogenous exergy

destruction ($\dot{E}_{D,k}^{UN,EN}$), and Unavoidable exogenous exergy destruction ($\dot{E}_{D,k}^{UN,EX}$) (Açikkalp et al., 2014).

The unavoidable endogenous exergy destruction ($\dot{E}_{D,k}^{UN,EN}$) within kth equipment is calculated by:

$$\dot{E}_{D,k}^{UN,EN} = \dot{E}_{D,k}^{EN} \left(\frac{\dot{E}_D}{\dot{E}_p}\right)_k^{UN} \quad (9)$$

Likewise, the other term can be calculated as below:

$$\dot{E}_{D,k}^{UN,EX} = \dot{E}_{D,k}^{UN} - \dot{E}_{D,k}^{UN,EN} \quad (10)$$

$$\dot{E}_{D,k}^{AV,EX} = \dot{E}_{D,k}^{EX} - \dot{E}_{D,k}^{UN,EX} \quad (11)$$

$$\dot{E}_{D,k}^{AV,EN} = \dot{E}_{D,k}^{EN} - \dot{E}_{D,k}^{UN,EN} \quad (12)$$

3.3. Conventional Exergoeconomic Analysis

The exergoeconomic analysis uses the unit cost of exergy and cost rates of all the different streams of material and exergy to calculate exergoeconomic variables for each equipment of the system (Ashouri et al., 2017). Table 6 presents equation of purchased equipment cost of system. Exergetic variables including exergy destruction rate $\dot{E}_{D,k}$ and exergetic efficiency ϵ_k are previously determined (Ghorbani, Mehrpooya, Hamed, & Amidpour, 2017).

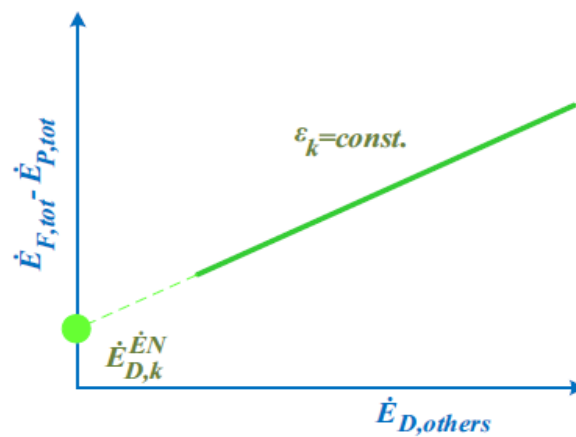


Figure 4. Illustration of engineering method (Mehrpooya & Shafaei, 2016)

Table.5. Presumption of advanced exergoeconomic analysis

Component	$\dot{Z}^{UN}$ (Operating conditions or $\dot{Z}_k\%$)
Compressor	90%
Multi stream heat exchanger	$\Delta T_{min} = 0.5^\circ\text{C}$
Air cooler	$\Delta T_{min} = 5^\circ\text{C}$

Definitions of cost rates of fuel $\dot{C}_f$ and product $\dot{C}_p$ result from definitions of the fuel and product for calculating the exergetic efficiency. $\dot{C}_{F,K}$ Represents the cost rate of exergy, into which the fuel exergy $\dot{E}_{F,K}$ is supplied for the

Kth equipment of the system, while $\dot{C}_{P,K}$ represents the cost rate related to the product exergy $\dot{E}_{P,K}$ for the same equipment (Bellos, Tzivanidis, & Antonopoulos, 2016).

Unit average exergy cost of fuel for the Kth equipment of the system represents the average cost at which the unit fuel exergy is supplied for the Kth equipment of the system (Bejan & Tsatsaronis, 1996):

$$c_{f,k} = \dot{C}_{F,K} / \dot{E}_{F,K} \quad (13)$$

Correspondingly, the unit cost of the product $C_{p,k}$ and the cost rate $\dot{C}_{D,K}$ associated with the exergy destruction $\dot{E}_{D,K}$ are expressed in the following equations:

$$c_{p,k} = \dot{C}_{P,K} / \dot{E}_{P,K} \quad (14)$$

$$\dot{C}_{D,K} = c_{f,k} \dot{E}_{D,K} \quad (15)$$

Exergy cost rate and unit average exergy cost rate as well as physical, chemical and total exergy rate for different streams of C3MR, MFC and DMR process are presented in Tables 7, 8 and 9, respectively.

The relative cost difference r_k between the average cost of the unit product exergy and unit fuel exergy is attained by the following relationship:

$$r_k = \frac{c_{p,k} - c_{f,k}}{c_{f,k}} = \frac{1 - \varepsilon_k}{\varepsilon_k} + \frac{\dot{Z}_k}{C_{F,K} \dot{E}_{P,K}} \quad (16)$$

The exergoeconomic factor represents the ratio of the investment cost to the sum of the investment, exergy destruction, and exergy lost cost.

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k} (\dot{E}_{D,k} + \dot{E}_{L,k})} \quad (17)$$

Exergoeconomic variables like $\dot{Z}_k^{CI}$ and $\dot{C}_{D,K}$ offer and absolute criterion for the degree of importance of the Kth equipment, while r_k and f_k offer relative criteria to evaluate the economic performance of an equipment (Ghorbani et al., 2017).

3.4. Advanced Exergoeconomic Analysis

Similarly to the exergy destruction rate, the endogenous and exogenous parts of the investment cost and the cost of the exergy destruction rate are related to the internal operating conditions and the equipment interactions, respectively. Furthermore, depending on whether the costs can be avoided, it can be divided into avoidable and unavoidable parts. The endogenous and exogenous along with avoidable and unavoidable cost rates associated with the exergy destruction of the kth equipment are (Petrakopoulou, Tsatsaronis, Morosuk, & Carassai, 2012):

$$\dot{C}_{D,k}^{EN} = c_{F,k} \dot{E}_{D,k}^{EN} \quad (18)$$

$$\dot{C}_{D,k}^{EX} = c_{F,k} \dot{E}_{D,k}^{EX} \quad (19)$$

$$\dot{C}_{D,k}^{UN} = c_{F,k} \dot{E}_{D,k}^{UN} \quad (20)$$

$$\dot{C}_{D,k}^{AV} = c_{F,k} \dot{E}_{D,k}^{AV} \quad (21)$$

The below equations have been concluded by combination of exergy destruction costs of endogenous/exogenous with avoidable/unavoidable (Moharamian, Soltani, Rosen, & Mahmoudi, 2018):

$$\dot{C}_{D,k}^{UN,EN} = c_{F,k} \dot{E}_{D,k}^{UN,EN} \quad (22)$$

$$\dot{C}_{D,k}^{UN,EX} = c_{F,k} \dot{E}_{D,k}^{UN,EX} \quad (23)$$

$$\dot{C}_{D,k}^{AV,EN} = c_{F,k} \dot{E}_{D,k}^{AV,EN} \quad (24)$$

$$\dot{C}_{D,k}^{AV,EX} = c_{F,k} \dot{E}_{D,k}^{AV,EX} \quad (25)$$

Investment costs of endogenous/exogenous and avoidable/unavoidable for equipment are calculated by following equations:

Table 6. Equation of the cost of the process

Component	Purchased equipment cost functions
Compressor	Cc= 7.90(HP) ^{0.62} Cc= Cost of Compressor (k\$)
Expander	CEx=0.378(HP) ^{0.81} CEx= Cost of Expander (k\$)
Heat exchanger	CE=a(V)b+c CE= Cost of Heat exchanger (\$)
Air cooler	CAC=1.218fmfpexp[a+blnQ+c(lnQ) ²] Q in KSCFM CAC=Cost of Air cooler (k\$) fm= Material factor fp= Pressure factor a=0.4692 , b=0.1203 , c=0.0931
Drum	CD=fmCb+Ca CD= Cost of Drum (\$) Cb=1.218exp[9.1-0.2889(lnW)+0.04576(lnW) ²] 5000<W<226000 lb shell weight Ca=300D ^{0.7396} L ^{0.7066} , 6<D<10 , 12<L<20 ft fm= Material factor
Absorber	C1=1.218(1.7Cb+23.9V1+Cp1) Cb=1.128exp[6.629+0.1826(logW)+0.02297(logW) ²] Cp1=300(D ^{0.7395})(L ^{0.7068}) C2=Cost of installed manholes, trays and nozzles C3=Cost of Cooler C4=Cost of Heater CAb=C1+C2+C3+C4 CAb= Cost of Absorber (\$)

$$\dot{Z}_k^{EN} = \dot{E}_{P,k}^{EN} \left(\frac{\dot{Z}}{\dot{E}_P} \right)_k^{\text{real}} \quad (26)$$

$$\dot{Z}_k^{EX} = \dot{Z}_k - \dot{Z}_k^{EN} \quad (27)$$

$$\dot{Z}_k^{UN} = \dot{E}_{P,k} \left(\frac{\dot{Z}}{\dot{E}_P} \right)_k^{\text{UN}} \quad (28)$$

$$\dot{Z}_k^{AV} = \dot{Z}_k - \dot{Z}_k^{UN} \quad (29)$$

Similarly to previous section, the following equations are derived by combination of irreversibility.

$$\dot{Z}_k^{UN,EN} = \dot{E}_{P,k}^{EN} \left(\frac{\dot{Z}}{\dot{E}_P} \right)_k^{\text{UN}} \quad (30)$$

$$\dot{Z}_k^{UN,EX} = \dot{Z}_k^{UN} - \dot{Z}_k^{UN,EN} \quad (31)$$

$$\dot{Z}_k^{AV,EN} = \dot{Z}_k^{EN} - \dot{Z}_k^{UN,EN} \quad (32)$$

$$\dot{Z}_k^{AV,EX} = \dot{Z}_k^{EX} - \dot{Z}_k^{UN,EX} \quad (33)$$

In advanced exergoeconomic analysis like the conventional exergoeconomic analysis can introduce and define parameters for comparing performance of equipment. These parameters can be calculated based on cost of the exergy destruction and avoidable endogenous of the investment cost.

$$\varepsilon_{\text{modified}} = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k} - \dot{E}_{D,k}^{UN} - \dot{E}_{D,k}^{AV,EX}} \quad (34)$$

$$f_k^{AV,EN} = \frac{\dot{Z}_k^{AV,EN}}{\dot{C}_{D,k}^{AV,EN} + \dot{Z}_k^{AV,EN}} \quad (35)$$

$$\dot{C}_{\text{tot}}^{AV,EN} = \dot{C}_{D,k}^{AV,EN} + \dot{Z}_k^{AV,EN} \quad (36)$$

4. Results and Discussion

4.1. Results of Conventional Exergy and Exergoeconomic Analyses

In Table 10, the results of the exergy and exergoeconomic analyses are presented for the equipment of the C3MR, MFC and DMR processes, respectively. The maximum and minimum amount of the irreversibility in C3MR process is related to compressor C5 with 15024 kW and compressor C1 with 663 kW, respectively. In MFC process, compressor C1 with 12661 kW has the highest amount of irreversibility and AC1 air cooler has the smallest one. In DMR process, HX3 heat exchanger with 20251 kW and HX1 heat exchanger with 1802 kW have the highest and smallest amount of irreversibility, respectively. In C3MR, MFC and DMR processes, AC3 air cooler with 98%, AC1 air cooler with 99.6% and HX2 heat exchanger with 87% have the

most amount of exergy efficiency, respectively. Results of exergoeconomic analysis show that the highest amount of exergy destruction cost is related to heat exchangers, so that in C3MR process HX5 heat exchanger with 3733 \$/h; in MFC process, HX3 heat exchanger with 2943 \$/h; and in DMR process, HX3 heat exchanger with 9824 \$/h have the highest amount of exergy destruction cost. In addition, in C3MR process, compressor C1 with 47 \$/h; in MFC process, AC1 air cooler with 20 \$/h; and in DMR process, compressor C2 with 225 \$/h; have the smallest amount of exergy destruction cost in comparison with other equipment. Exergoeconomic factor is considered as an important parameter in process analysis. When this parameter for a component is high, for decreasing the process cost, investment cost should be decreased. On the other hand, if exergoeconomic factor for a component is small, for decreasing the process cost, equipment efficiency should be increased. In C3MR process, the highest value of exergoeconomic factor is related to compressor C1 with 63.7% and the smallest one is related to HX5 heat exchanger with 0.4%. In MFC process, AC1 air cooler with 90% and HX3 heat exchanger with 0.4% have the highest and smallest amount of exergoeconomic factor, respectively. In DMR process, the highest value of this factor is related to compressor C2 with 55.5% and the smallest one is related to HX3 heat exchanger with 0.2%. Generally it can be concluded that compressors and air coolers have the greatest value of exergoeconomic factor among the equipment. Therefore, investment cost should be decreased for decreasing the process cost.

4.2. Results of advanced exergy and exergoeconomic analyses

Table 11 illustrates the advanced exergy destruction analysis of the C3MR, MFC and DMR processes. Generally in compressors the amount of avoidable exergy destruction is greater than unavoidable part, while in air coolers and heat exchangers the amount of unavoidable exergy destruction is higher than the avoidable one. Except for compressor C4 and AC2 air cooler in C3MR process and compressor C6 and AC1 air cooler in MFC process, in the rest of the equipment the endogenous exergy destruction is greater than the exogenous part. This issue indicates that the most source of the irreversibility belongs to

the equipment by them, not the interaction between the equipment. According to the avoidable endogenous exergy destruction part, in C3MR process, Compressor C5 with 9730 kW, in MFC process, compressor C1 with 6342 kW and in DMR process, compressor C3 with 10008 kW have the highest amount of avoidable endogenous exergy destruction in comparison with other equipment. Consequently, improving the efficiency of these equipment can reduce the irreversibility significantly.

Table 12 shows the analysis of the advanced exergy destruction cost rates. In all three processes, the amount of avoidable exergy destruction cost is higher than unavoidable one for compressors, while in air coolers and heat exchangers the unavoidable part of exergy destruction cost has greater amount. Except for compressor C4 and AC2 air cooler in C3MR process, and compressor C6 and AC1 air cooler in MFC process, in the rest of the equipment the endogenous exergy destruction cost is greater than the exogenous part. Based on results of avoidable endogenous exergy destruction cost rates, in C3MR process, HX2 heat exchanger with 1121 \$/h, in MFC process, compressor C1 with 450 \$/h and in DMR process, HX3 heat exchanger with 3955 \$/h have the highest cost of avoidable endogenous exergy destruction. Therefore, improving performance of these equipment has great impact on decreasing the irreversibility costs. Also, the charts related to four categories of exergy destruction cost i.e. unavoidable endogenous, unavoidable exogenous, avoidable endogenous and avoidable exogenous, for C3MR, MFC and DMR process has been shown in Figures 5, 6 and 7, respectively.

Table 13 shows the analysis of the advanced investment cost for each component of these three processes. In all the equipment the unavoidable investment cost is greater than the avoidable part. In addition, except for compressor C4 and AC2 air cooler in C3MR process, in the rest of the equipment the endogenous investment cost is greater than the exogenous part. The results of avoidable endogenous investment cost show that in C3MR process, compressor C5 with 71\$/h, in MFC process, compressor C6 with 57 \$/h and in DMR process, compressor C3 with 56.7 \$/h have the greatest amount of avoidable endogenous investment cost among the other equipment.

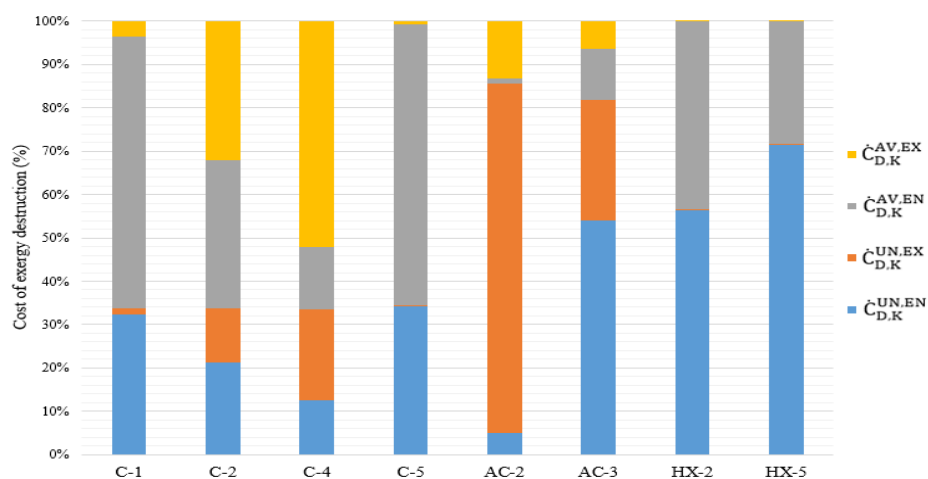


Figure 5. Dividing of exergy destruction equipment cost into avoidable/unavoidable endogenous/exogenous: C3MR process

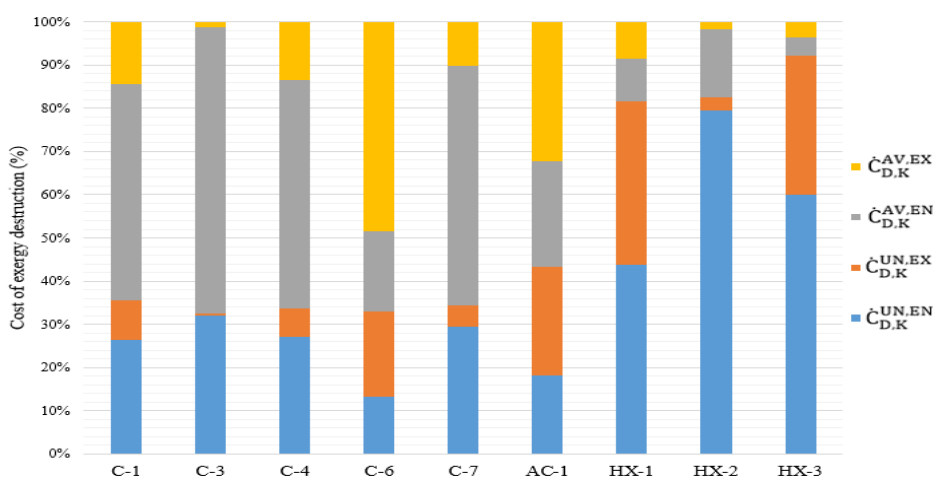


Figure 6. Dividing of exergy destruction equipment cost into avoidable/unavoidable endogenous/exogenous: MFC process

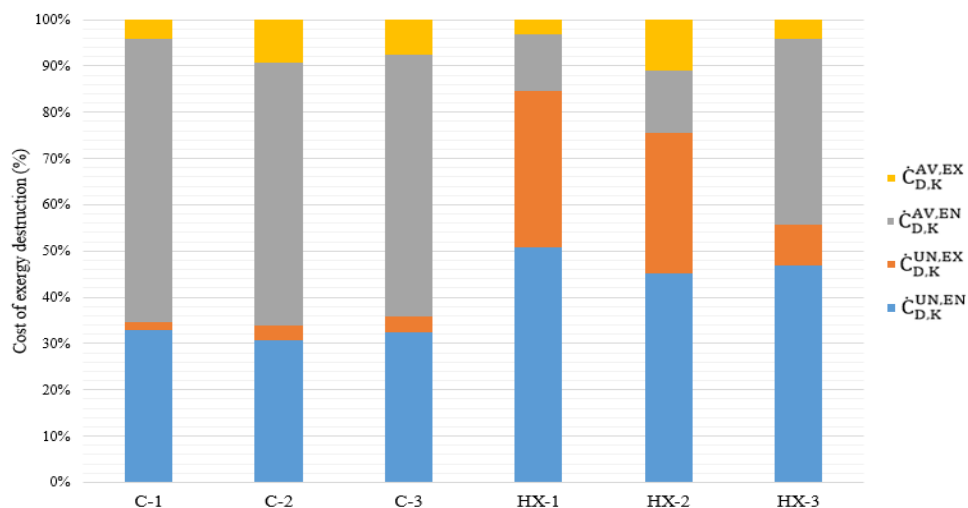


Figure 7. Dividing of exergy destruction equipment cost into avoidable/unavoidable endogenous/exogenous: DMR process

In Table 14, the comparison between some of the parameters for the conventional and advanced exergy and exergoeconomic analyses is performed. In all of three processes, modified exergy efficiency for all equipment is higher than exergy efficiency. Due to the total cost of exergy destruction, in C3MR process, the performance of the HX2 and HX5 heat exchangers should be considered and amended, respectively, since they have the highest amount of total costs by 1126 \$/h and 1062 \$/h, respectively. In MFC process, the performance of the compressor C1 and HX2 heat exchanger should be modified, respectively. Because these equipment with 504.7 \$/h and 435.7 \$/h have the greatest amount of total costs, respectively. In DMR process, the performance of the HX3 heat exchanger and compressor C3 should be modified, respectively. Since, they have the highest amount of total costs by 3963 \$/h and 767 \$/h, respectively. In advanced analysis, compressor C4 and AC2 air cooler have the highest and lowest amount of exergoeconomic factor, respectively for C3MR process. In MFC process, compressor C6 and HX2 heat exchanger have the maximum and minimum amount of exergoeconomic factor, respectively. In DMR process, compressor C2 and HX3 heat exchanger have the highest and lowest amount of exergoeconomic factor, respectively.

Three strategies are available to reduce the cost of avoidable exergy destruction as shown in Table 15. When the cost of avoidable exergy destruction for equipment in the system is high, there is a good potential for improvement in the system performance. It can be improved by either improving its performance or replacing it with a high-performed component. In this way, system performance has been improved and the rate of irreversibility is reduced. This method is a strategy considered here for all equipment of these processes, except for compressor C4 and AC2 air cooler in C3MR process and compressor C6 in MFC process. In strategy B, the irreversibility of the desired component can be reduced by increasing the efficiency of the other equipment. This strategy is used when the rate of avoidable exogenous exergy destruction cost is significant compared to the endogenous portion. For example, in C3MR process, compressors C2 and C4 as well as the AC2 and AC3 air coolers; in MFC process, compressors C1 and C6, AC1 air cooler and HX1 and HX3 heat exchangers; in DMR process, compressor C3 and HX1, HX2 and HX3 heat exchangers have this feature and this strategy can be used for these components. Finally, strategy C is

used when the cost of avoidable exogenous exergy destruction is significant and at least is about half of the total cost of avoidable exergy destruction. In this strategy, the system's structural optimization should reduce the irreversibility of the system. As it can be seen, strategy C can be used for the compressors C2 and C4 in C3MR process; compressors C1 and C6 as well as HX1 and HX3 heat exchangers in MFC process; and HX2 and HX3 heat exchangers in DMR process.

5. Sensitivity analysis

A sensitivity analysis of the system key parameters, including compressors compression ratio and pressure drop in expansion valves, has been carried out for determining the influence of thermodynamic parameters on the system performance.

Inasmuch as advanced exergoeconomic analysis has not been carried out in the integrated structure of LNG / NGL / NRU, the presented integrated structure should be validated with the similar structures. As shown in Fig. 8, the amount of specific power for the integrated processes developed in this article is less than the previous research, which indicates the high degree of process design in this paper. For example, the amount of specific power in the MFC process in this article has decreased by about 19% compared to the reference (Ghorbani, Shirmohammadi, Mehrpooya, & Mafi, 2018). Furthermore, the amount of specific power in the DMR process in this paper is about 16% lower than the reference (Vatani, Mehrpooya, & Tirandazi, 2013), which indicates the acceptable accuracy in designing and integrating the proposed structures. Moreover, according to Fig. 9, the LNG and NGL prices in the structures presented in this paper is higher than other previous studies, because in the structures presented in this paper a certain amount cost is spent for nitrogen separation. While in the same LNG / NGL structures, the inlet gas does not contain nitrogen. Following references are employed for comparison and validation presented in figures 8 and 9: (Ansarinassab & Mehrpooya, 2017a, 2017b; Ghorbani, Shirmohammadi, Mehrpooya, & Mafi, 2018; Khan, Chaniago, Getu, & Lee, 2014; Mak & Graham, 2007; Mehrpooya & Ansarinassab, 2015a, 2015b; Mehrpooya, Hossieni, & Vatani, 2014; Peters, Timmerhaus, West, Timmerhaus, & West, 1968; Qualls et al.,

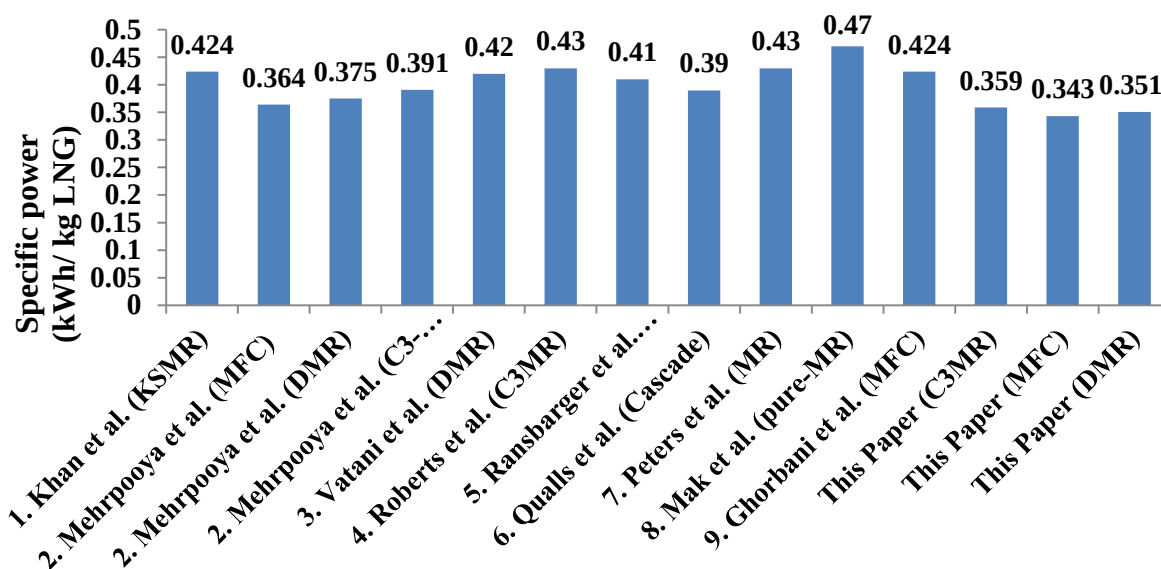


Figure 8. Specific power value in the developed integrated structures and its comparison with other references

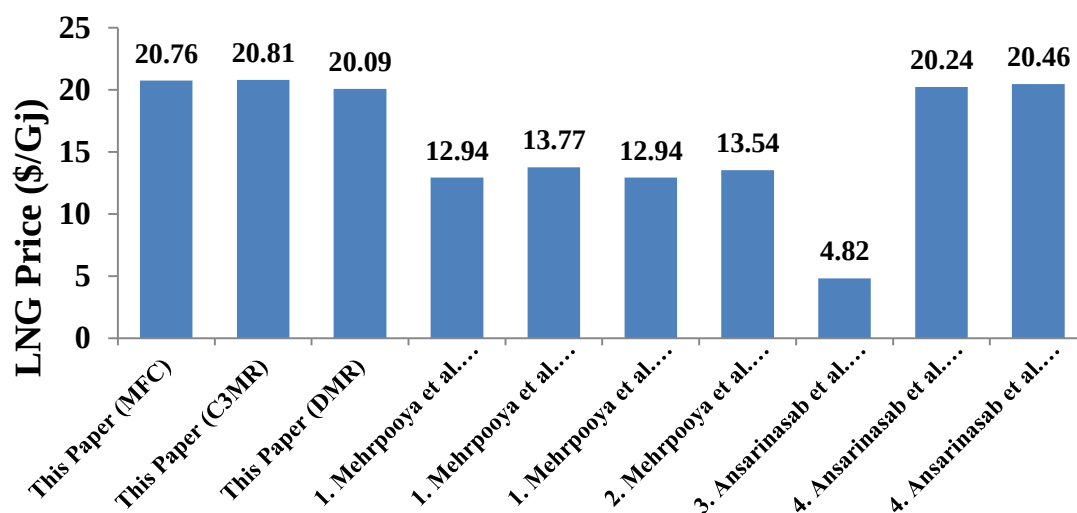


Figure 9. LNG price in the developed integrated structures and its comparison with other references

2006; Ransbarger, 2006; Roberts & Rowles, 2003; Vatani, Mehrpooya, & Tirandazi, 2013) Fig 10 represents the variation of LNG price and NGL price with respect to pressure ratio of compressor C4 in C3MR process. It can be seen that the surging in pressure ratio of compressor C4 decreases the LNG price and increases the NGL price. Variation of LNG price and NGL price with respect to pressure ratio of compressor C3 and pressure drop of expansion valve V1 in the MFC process are shown in Figures 11 and 12, respectively. The LNG price decreases by surging in the both pressure ratio of compressor C3 and pressure drop of expansion valve V1, whereas NGL price increases. The same is true for the C3MR

process. Figures 13 and 14 show variation of LNG price and NGL price with respect to pressure ratio of compressor C4 and pressure drop of expansion valve V2 in the DMR process, respectively. Unlike the two previous processes, higher pressure ratio in compressor and higher pressure drop in expansion valve, leads to obtaining higher LNG price and lower NGL price.

Results obtained from sensitivity analysis of the integrated structures developed in this paper which are shown in Figures 10 through 14, are function of the design of integrated process structures and all in line with previous research which presented in references (Mehrpooya & Ansarinasab, 2015a, 2015b; Ansarinasab & Mehrpooya, 2017a, 2017b).

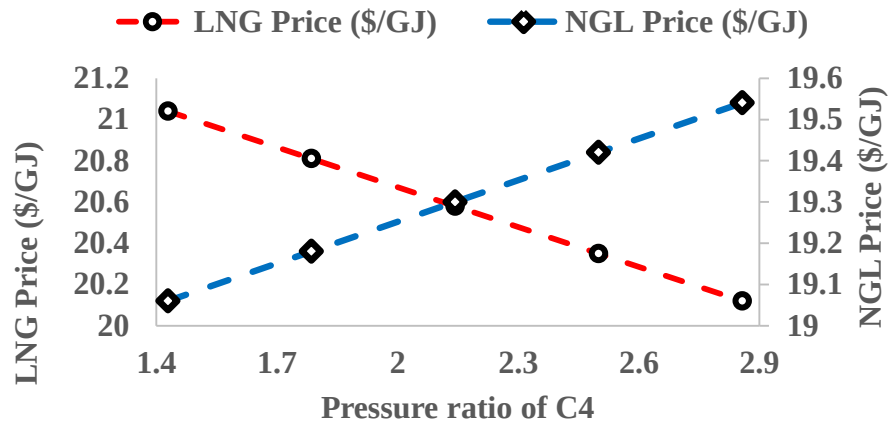


Figure 10. Variation of LNG price and NGL price with respect to pressure ratio of compressor C4 in C3MR process

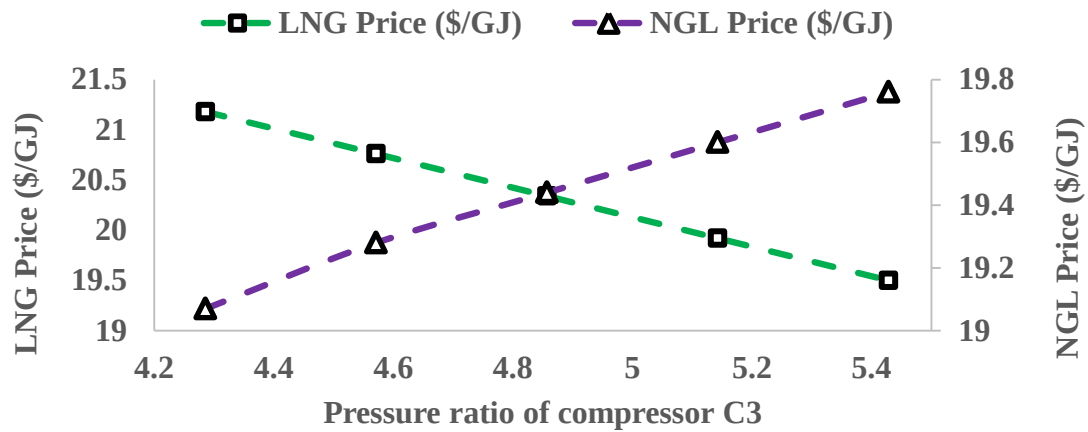


Figure 11. Variation of LNG price and NGL price with respect to pressure ratio of compressor C3 in MFC process

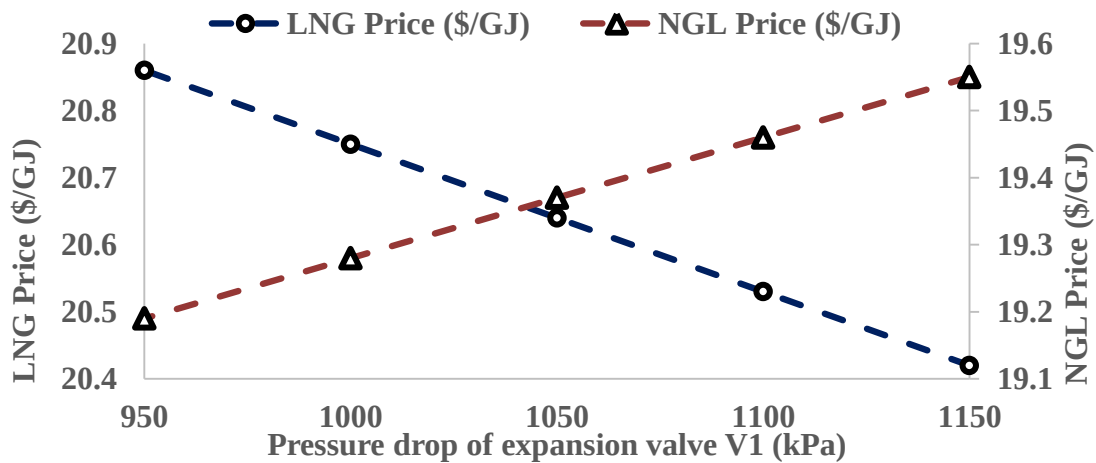


Figure 12. Variation of LNG price and NGL price with respect to pressure drop of expansion valve V1 in MFC process

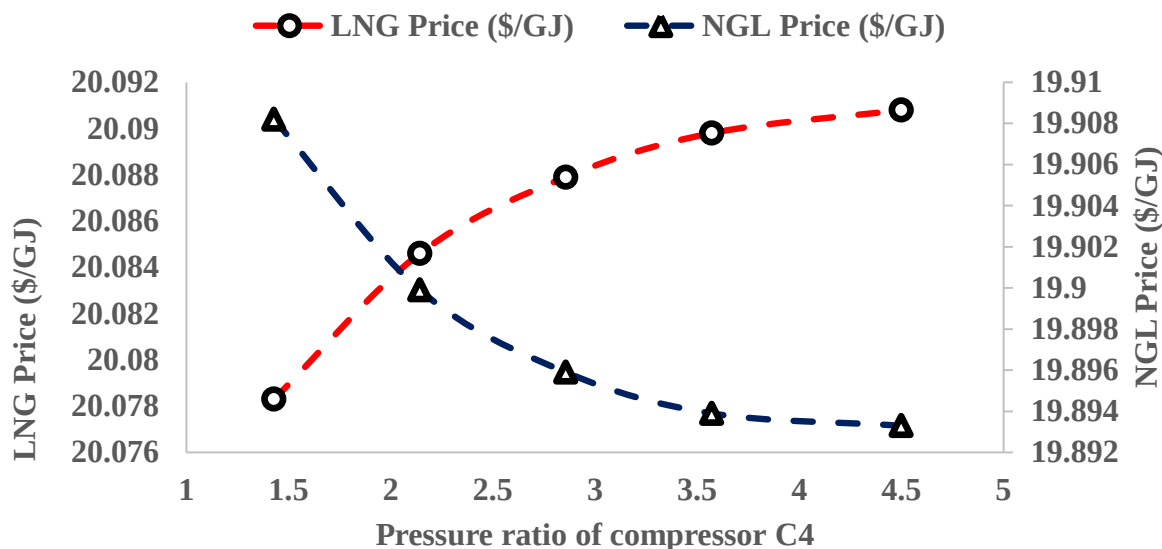


Figure 13. Variation of LNG price and NGL price with respect to pressure ratio of compressor C4 in DMR process

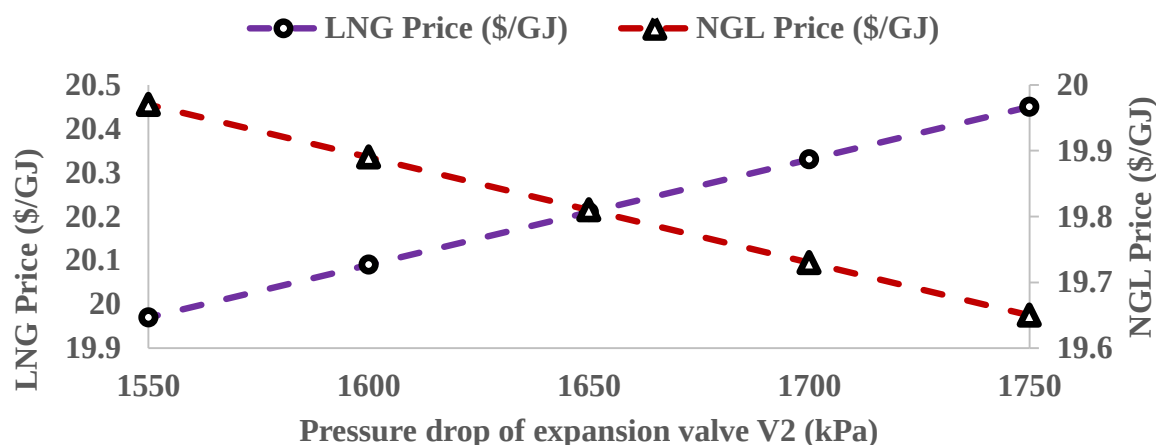


Figure 14. Variation of LNG price and NGL price with respect to pressure drop of expansion valve V2 in DMR process

6. Conclusion

Comprehensive exergy and exergoeconomic analyses as well as advanced exergy and exergoeconomic analyses for the first time have been employed for malfunction diagnosis of C3MR, MFC, and DMR processes in an integrated cryogenic structure. Additionally sensitivity analysis is also conducted for the cryogenic system. Following results have been obtained from the conventional, advanced and sensitivity analyses:

- According to the results of exergy analysis, in C3MR process, AC3 air cooler with 98%; in MFC process, AC1 air cooler with 99.6%; in DMR process, HX2 heat exchanger with 87%; have

the most amount of exergetic efficiency among the other equipment.

- According to advanced exergy analysis, just in compressors the avoidable part of exergy destruction is higher than the unavoidable part. In addition, in all of three processes, compressors have the highest amount of avoidable endogenous exergy destruction.
- Based on the results of advanced exergoeconomic analysis, in C3MR process, HX2 heat exchanger with 1121 \$/h; in MFC process, compressor C1 with 450 \$/h; and in DMR process, HX3 heat exchanger with 3955 \$/h; have the greatest amount of avoidable endogenous exergy destruction cost. Furthermore, in all of three processes,

compressors have the highest amount of avoidable endogenous investment cost. Thus, improving the performance of these equipments will have a significant impact on cost reduction.

- According to the total costs for the equipment, in C3MR process, HX2 heat exchanger with 1126 \$/h should be considered in the first priority and modified. In MFC process, compressor C1 with 504.7 \$/h should be considered and modified. In DMR process, the

performance of HX3 heat exchanger with 3963 \$/h should be improved.

- Comparison the results of this research with previous studies shows that the amount of specific power in the integrated processes developed in this article has been less than previous studies which indicates the acceptable accuracy in designing and integrating of the proposed structures.
- Results obtained from sensitivity analysis are in line with previous researches.

Table 7. Results of exergy and unit exergy cost of C3MR process

Stream	$\dot{E}_{PH}$ (kW)	$\dot{E}_{CH}$ (kW)	$\dot{E}_{TOT}$ (kW)	$\dot{C}$ (\$/h)	c (\$/GJ)	Stream	$\dot{E}_{PH}$ (kW)	$\dot{E}_{CH}$ (kW)	$\dot{E}_{TOT}$ (kW)	$\dot{C}$ (\$/h)	c (\$/GJ)
Feed gas	37575.23	6750765.03	6788340.26	12321.00	0.50	200	36536.71	15022156.95	15058693.65	11756783.58	216.87
101	37696.40	6750765.03	6788461.43	12597.21	0.52	201	34193.23	15022156.95	15056350.17	11756783.58	216.90
102	38282.79	6750765.03	6789047.82	13403.32	0.55	204	8254.94	3385078.62	3393333.56	2649725.54	216.91
103	39753.65	6750765.03	6790518.68	14851.16	0.61	206	6274.71	3385078.62	3391353.33	2648170.94	216.91
106	14974.12	1919650.29	1934624.41	4233.92	0.61	209	11765.43	4488906.28	4500671.71	3514784.99	216.93
108	19936.54	2879475.43	2899411.97	6532.96	0.63	212	5451.09	2112426.48	2117877.58	1654015.15	216.94
109	617.16	585570.14	586187.30	1282.87	0.61	214	185.12	1919442.75	1919627.86	1499215.09	216.94
111	1262.14	1366330.33	1367592.47	2993.36	0.61	216	228.27	2112426.48	2112654.76	1649973.55	216.94
112	18944.47	1919650.29	1938594.76	5489.22	0.79	217	2130.10	2112426.48	2114556.59	1650238.40	216.78
113	18413.98	1919650.29	1938064.27	5489.22	0.79	219	13843.96	7898516.78	7912360.74	6173835.87	216.74
114	698.64	585570.14	586268.78	1308.63	0.62	220	26502.46	15022156.95	15048659.40	11746514.62	216.82
115	626.91	585570.14	586197.05	1308.63	0.62	221	42747.42	15022156.95	15064904.36	11748307.50	216.62
116	32403.37	2711668.94	2744072.31	11634.57	1.18	300	88466.90	10320782.62	10409249.52	3076630.59	82.10
117	28658.93	2712193.19	2740852.12	11634.57	1.18	302	92830.20	10320782.62	10413612.83	3083139.44	82.24
118	37772.26	2712193.19	2749965.44	14515.93	1.47	304	62542.78	4907075.22	4969618.00	1472270.95	82.29
119	29299.26	38750.49	68049.75	608.38	2.48	308	40702.30	5418668.50	5459370.80	1618162.65	82.33
120	27541.30	36425.46	63966.76	571.87	2.48	310	22428.85	10320782.62	10343211.48	3068730.13	82.41
122	1406.10	2325.03	3731.13	33.36	2.48	311	127056.80	4907075.22	5034132.01	1493664.09	82.42
126	48286.27	36425.46	84711.73	7988.74	26.20	313	49628.01	4907075.22	4956703.22	1472052.84	82.50
127	60723.85	3498430.85	3559154.70	31819.35	2.48	314	82339.71	10320782.62	10403122.33	3074720.47	82.10
128	54623.28	3498430.85	3553054.13	31764.85	2.48	315	76271.57	10320782.62	10397054.19	3074871.75	82.15
130	1054.73	97974.12	99028.84	881.82	2.47	Side1	4889.27	1601590.50	1606479.77	6811.30	1.18
131	906.77	97974.12	98880.88	880.50	2.47	Side2	5108.06	1526907.32	1532015.38	6495.58	1.18
134	13267.79	690232.76	703500.55	8300.26	3.28	Side3	6129.49	1398715.56	1404845.05	5956.40	1.18
135	46351.61	2729202.67	2775554.29	24715.40	2.47	Side1R	4816.62	1601590.50	1606407.12	6811.00	1.18
136	26568.33	2729202.67	2755771.00	18460.53	1.86	Side2R	5149.82	1526907.32	1532057.14	6495.76	1.18
137	28450.64	2729202.67	2757653.32	18765.97	1.89	Side3R	5620.61	1398715.56	1404336.17	5954.24	1.18
138	48383.56	2729202.67	2777586.23	25068.14	2.51	NGL	2243.99	1278778.30	1281022.29	5431.40	19.18
139	58217.76	2729202.67	2787420.44	28584.12	2.85	LNG	57770.03	2729202.67	2786972.70	28223.86	20.81
140	57770.03	2729202.67	2786972.70	28584.12	2.85	Nitrogen	1117.42	2325.03	3442.45	30.78	2.48

Table 8. Results of exergy and unit exergy cost of MFC process

Stream	$\dot{E}_{PH}$ (kW)	$\dot{E}_{CH}$ (kW)	$\dot{E}_{TOT}$ (kW)	$\dot{C}$ (\$/h)	c (\$/GJ)	Stream	$\dot{E}_{PH}$ (kW)	$\dot{E}_{CH}$ (kW)	$\dot{E}_{TOT}$ (kW)	$\dot{C}$ (\$/h)	c (\$/GJ)
Feed gas	37575.23	6750765	6788340	634723	25.97	200	39355.95	7744425	7783781	4554003	162.52
101	37635.72	6750765	6788401	634864.5	25.98	203	54625.40	7744425	7799050	4570469	162.79
103	37226.86	5173680	5210907	488464.6	26.04	204	53681.77	7744425	7798107	4570469	162.81
104	1356.56	1577263	1578620	147977.9	26.04	206	23502.12	7744425	7767927	4551614	162.76
105	18613.43	2586840	2605454	244232.3	26.04	207	32866.38	7744425	7777291	4552776	162.61
106	18613.43	2586840	2605454	244232.3	26.04	208	32903.44	7744425	7777328	4552964	162.62
107	16204.49	2586840	2603045	244363.5	26.08	209	40728.29	7744425	7785153	4553911	162.49
108	23688.30	2586840	2610528	247842.2	26.37	300	83515.58	8303601	8387117	3361008	111.32
109	406.97	473179	473586	44393.36	26.04	301	83669.08	8303601	8387270	3361367	111.33
110	949.59	1104084	1105034	103584.5	26.04	302	86445.11	8303601	8390046	3365150	111.41
111	798.15	1104084	1104883	103584.5	26.04	304	190776.72	8303601	8494378	3415838	111.70
112	471.42	473179	473650.5	44439.21	26.06	305	187617.77	8303601	8491219	3415838	111.74
113	408.39	473179	473587.4	44439.21	26.07	308	80016.17	8303601	8383617	3360186	111.33
114	22948.08	2586840	2609788	247842.2	26.38	309	83823.71	8303601	8387425	3360820	111.30
115	32367.92	2716187	2748555	438130.9	44.28	400	41953.18	16621896	16663849	22713317	378.62
116	28589.56	2716187	2744777	438130.9	44.34	402	21088.32	8310948	8332036	11356920	378.62
117	38536.48	2716187	2754723	442808.2	44.65	404	22580.15	8310948	8333528	11362678	378.75
118	59526.51	3434830	3494357	573965.4	45.63	406	17363.11	8310948	8328311	11347352	378.47
119	53945.68	3434830	3488776	569995.7	45.38	407	21088.32	8310948	8332036	11356920	378.62
120	29197.43	14283.14	43480.57	7141.9	45.63	409	17663.58	8310948	8328612	11352758	378.64
121	27445.59	13426.15	40871.73	6713.385	45.63	411	51868.73	16621896	16673765	22702059	378.21
122	47791.42	13426.15	61217.57	16280.73	73.87	Side1	7498.65	2254312	2261811	360542	44.28
123	7746.42	718797.5	726543.9	118681.2	45.38	Side2	7917.92	2137319	2145237	341959.9	44.28
124	962.88	89346.53	90309.41	14752.15	45.38	Side3	8490.64	1770925	1779416	283646.6	44.28
125	827.84	89346.53	90174.37	14656.09	45.15	Side1R	7377.92	2254312	2261690	360523.2	44.28
126	6783.54	629451	636234.5	103929.1	45.38	Side2R	7981.04	2137319	2145300	341970.2	44.28
127	12115.22	629451	641566.2	106436.2	46.08	Side3R	8704.94	1770925	1779630	283680.4	44.28
128	12113.03	629451	641564	106436.2	46.08	NGL	2168.34	1271611	1273780	203046	19.89
129	46117.21	2717083	2763201	451370.3	45.38	LNG	56172.09	2677398	2733570	450322.5	20.04
130	25529.80	2717083	2742613	441689.4	44.74	Nitrogen	1137.14	856.9882	1994.13	115.9424	2.15

Table 9. Results of exergy and unit exergy cost of DMR process

Stream	$\dot{E}_{PH}$ (kW)	$\dot{E}_{CH}$ (kW)	$\dot{E}_{TOT}$ (kW)	$\dot{C}$ (\$/h)	c (\$/GJ)	Stream	$\dot{E}_{PH}$ (kW)	$\dot{E}_{CH}$ (kW)	$\dot{E}_{TOT}$ (kW)	$\dot{C}$ (\$/h)	c (\$/GJ)
Feed gas	36487.95	4771470	4807958	339076	19.59	139	56942.16	2682143	2739085	208188	21.11
101	36652.92	4771470	4808123	339501.9	19.61	200	47684.55	17248673	17296357	19269377	309.46
102	38306.43	4771470	4809777	341486.5	19.72	201	48451.94	17248673	17297125	19271358	309.48
103	34340.71	2866506	2900847	205978.1	19.72	202	21318.86	7589416	7610735	8479427	309.48
104	3537.02	1905393	1908930	135545.8	19.72	203	20978.21	7589416	7610394	8479427	309.50
105	13736.28	1146602	1160339	82391.25	19.72	204	17774.41	7589416	7607190	8475815	309.50
106	20604.43	1719904	1740508	123586.8	19.72	205	27133.09	9659257	9686390	10791931	309.48
107	1061.10	571617.8	572678.9	40663.74	19.72	206	29761.12	9659257	9689018	10795085	309.49
108	2475.91	1333775	1336251	94882.04	19.72	207	29104.97	9659257	9688362	10795085	309.51
109	18069.74	1719904	1737973	123794.4	19.79	208	12931.34	9659257	9672188	10777126	309.51
110	1177.01	571617.8	572794.8	40735.43	19.75	210	22729.22	9659257	9681986	10778119	309.23
111	2118.56	1333775	1335893	94882.04	19.73	211	40460.20	17248673	17289133	19253934	309.35
112	1028.40	571617.8	572646.2	40735.43	19.76	212	57419.75	17248673	17306092	19255733	309.07
113	17333.64	1146602	1163936	84616.35	20.19	300	81662.69	13252249	13333911	6445903	134.28
114	16783.08	1146602	1163386	84616.35	20.20	302	93442.79	13252249	13345691	6460833	134.48
116	28546.78	2703464	2732010	187308.6	19.04	304	48429.87	6784329	6832759	3310182	134.57
117	37610.08	2703464	2741074	192293	19.49	305	47492.88	6784329	6831822	3310182	134.59
118	54607.13	3168351	3222959	241845.7	20.84	309	138424.43	6473866	6612291	3211394	134.91
119	31175.82	307912.3	339088.1	25444.61	20.84	311	112719.95	13252249	13364969	6483761	134.76
121	54651.30	289437.6	344088.9	37857.01	30.56	313	18983.26	13252249	13271232	6438006	134.75
122	1870.55	18474.74	20345.29	1526.679	20.84	314	87616.42	13252249	13339865	6445041	134.21
123	1581.39	18474.74	20056.13	1367.656	18.94	Side1	3571.97	2325335	2328907	159453.1	19.02
124	1300.77	18474.74	19775.51	1194.082	16.77	Side2	3681.83	2415270	2418952	165618.3	19.02
125	1260.65	18474.74	19735.39	1145.927	16.13	Side3	5126.60	2132947	2138074	146387.2	19.02
127	50886.10	3168351	3219238	239799.3	20.69	Side1R	3561.12	2325335	2328896	159452.4	19.02
128	5180.94	481248.9	486429.9	36300.67	20.73	Side2R	3613.48	2415270	2418884	165613.5	19.02
129	643.99	59819.24	60463.23	4512.165	20.73	Side3R	4140.30	2132947	2137088	146319.7	19.02
130	4536.95	421429.7	425966.6	31788.5	20.73	NGL	2468.46	2298897	2301365	157567.3	19.02
131	553.65	59819.24	60372.89	4456.285	20.50	LNG	56941.67	2682143	2739085	204859.8	20.78
134	45548.85	2682143	2727692	203558.4	20.73	Nitrogen	1251.21	18474.74	19725.95	1121.566	2.79

Table.10. Exergy and exergoeconomic analyses results for integrated structure

Component	$\dot{E}_F$ (kW)	$\dot{E}_P$ (kW)	$\dot{E}_D$ (kW)	c_F (\$/Gj)	c_P (\$/Gj)	$\dot{C}_D$ (\$/h)	$\dot{Z}_k$ (\$/h)	ε (%)	yD (%)	r (%)	f (%)
C3MR process											
C-1	2565.13	1901.83	663.30	19.72	38.68	47.09	82.75	74.14	0.129	96.17	63.73
C-2	9571.04	7173.02	2398.02	19.72	33.56	170.24	187.20	74.94	0.467	70.19	52.37
C-4	3022.15	1882.31	1139.83	19.72	45.18	80.92	91.60	62.28	0.222	129.10	53.10
C-5	74935.39	59910.85	15024.53	19.72	27.77	1066.62	670.52	79.95	2.93	40.84	38.60
AC-2	82375.42	78806.79	3568.63	19.72	21.14	253.34	148.75	95.67	0.695	7.19	36.99
AC-3	90995.70	89297.25	1698.45	19.72	20.56	120.58	148.75	98.13	0.331	4.25	55.23
HX-2	7677.48	4385.36	3292.12	217.69	381.86	2579.98	11.79	57.12	0.641	75.41	0.46
HX-5	73128.99	60497.00	12631.99	82.10	99.31	3733.58	14.87	82.73	2.46	20.96	0.40
MFC process											
C-1	58197.62	45536.27	12661.34	19.72	29.20	898.85	654.78	78.24	5.31	48.06	42.14
C-3	9641.83	7001.34	2640.49	19.72	36.46	187.45	234.60	72.61	1.11	84.91	55.58
C-4	12489.24	9364.26	3124.98	19.72	34.47	221.85	275.42	74.98	1.31	74.80	55.39
C-6	8759.61	6629.59	2130.02	19.72	35.32	151.21	221.05	75.68	0.894	79.10	59.38
C-7	21953.31	17245.50	4707.81	19.72	31.40	334.22	390.73	78.56	1.97	59.21	53.90
AC-1	83859.42	83575.71	283.71	19.72	20.40	20.14	185.57	99.66	0.112	3.47	90.21
HX-1	3156.48	1796.19	1360.29	367.90	649.56	1801.63	19.65	56.90	0.571	76.56	1.08
HX-2	11569.22	9593.59	1975.63	387.16	467.63	2753.62	25.58	82.92	0.829	20.78	0.920
HX-3	28695.11	23676.67	5018.44	162.94	197.59	2943.66	10.02	82.51	2.11	21.27	0.339
DMR process											
C-1	21586.9	16959.54	4627.36	19.72	29.47	328.51	266.72	78.56	1.48	49.44	44.81
C-2	13048.16	9881.116	3167.05	19.72	33.93	224.84	280.73	75.73	1.01	72.07	55.53
C-3	86340.62	68633.15	17707.47	19.72	28.47	1257.09	905.96	79.49	5.66	44.39	41.88
HX-1	3214.644	1412.231	1802.41	312.20	717.15	2025.76	33.04	43.93	0.576	129.71	1.60
HX-2	17228.28	15052.24	2176.04	290.73	333.40	2277.47	34.85	87.37	0.696	14.68	1.51
HX-3	93339.94	73088.99	20250.95	134.75	172.17	9823.81	20.64	78.30	6.48	27.77	0.210

Table 11. Values of advanced exergy destruction for integrated structure

Component	$\dot{E}_D$ (kW)	$\dot{E}_{D,k}^{UN}$ (kW)	$\dot{E}_{D,k}^{AV}$ (kW)	$\dot{E}_{D,k}^{EN}$ (kW)	$\dot{E}_{D,k}^{EX}$ (kW)	$\dot{E}_{D,k}^{UN,EN}$ (kW)	$\dot{E}_{D,k}^{UN,EX}$ (kW)	$\dot{E}_{D,k}^{AV,EN}$ (kW)	$\dot{E}_{D,k}^{AV,EX}$ (kW)
C3MR process									
C-1	663.31	223.47	439.84	630.06	33.25	214.33	9.14	415.73	24.11
C-2	2398.02	806.88	1591.14	1334.30	1063.72	512.33	294.55	821.97	769.17
C-4	1139.83	383.26	756.56	306.15	833.68	142.85	240.42	163.30	593.26
C-5	15024.53	5165.91	9858.63	14879.00	145.53	5149.09	16.82	9729.91	128.72
AC-2	3568.63	3055.64	512.99	215.73	3352.90	175.74	2879.90	39.99	473.00
AC-3	1698.448	1387.27	311.18	1120.20	578.25	917.44	469.83	202.76	108.41
HX-2	3292.121	1859.71	1432.41	3289.90	2.22	1858.60	1.12	1431.30	1.10
HX-5	12631.99	9046.42	3585.56	12618.00	13.99	9036.37	10.05	3581.63	3.93
MFC process									
C-1	12661.34	4490.98	8170.36	9679.80	2981.54	3337.84	1153.14	6341.96	1828.40
C-3	2640.49	860.38	1780.11	2592.90	47.59	846.89	13.49	1746.01	34.10
C-4	3124.98	1054.50	2070.47	2494.30	630.68	846.28	208.23	1648.02	422.45
C-6	2130.02	701.89	1428.14	677.07	1452.95	283.29	418.59	393.78	1034.36
C-7	4707.81	1616.67	3091.15	3995.70	712.11	1381.88	234.78	2613.82	477.33
AC-1	283.71	123.43	160.28	120.86	162.85	51.67	71.53	69.19	91.32
HX-1	1360.29	1111.38	248.91	728.80	631.49	595.09	516.29	133.71	115.20
HX-2	1975.63	1629.76	345.87	1882.50	93.13	1570.48	59.27	312.02	33.86
HX-3	5018.44	4620.73	397.72	3233.60	1784.84	3016.11	1604.61	217.49	180.23
DMR process									
C-1	4627.36	1602.11	3025.26	4361.50	265.86	1528.78	73.32	2832.72	192.54
C-2	3167.05	1073.88	2093.17	2767.30	399.75	971.14	102.74	1796.16	297.00
C-3	17707.47	6345.26	11362.21	15740.00	1967.47	5731.55	613.70	10008.45	1353.76
HX-1	1802.41	1523.83	278.58	1139.30	663.11	917.55	606.28	221.75	56.84
HX-2	2176.04	1642.34	533.70	1276.40	899.64	982.73	659.61	293.67	240.03
HX-3	20250.95	11260.82	8990.13	17627.00	2623.95	9474.27	1786.55	8152.73	837.40

Table 12. Values of advanced exergy destruction cost for integrated structure

Component	$\dot{C}_D$ (\$/h)	$\dot{C}_{D,K}^{UN}$ (\$/h)	$\dot{C}_{D,K}^{AV}$ (\$/h)	$\dot{C}_{D,K}^{EN}$ (\$/h)	$\dot{C}_{D,K}^{EX}$ (\$/h)	$\dot{C}_{D,K}^{UN,EN}$ (\$/h)	$\dot{C}_{D,K}^{UN,EX}$ (\$/h)	$\dot{C}_{D,K}^{AV,EN}$ (\$/h)	$\dot{C}_{D,K}^{AV,EX}$ (\$/h)
C3MR process									
C-1	47.09	15.86	31.23	44.73	2.36	15.22	0.65	29.51	1.71
C-2	170.24	57.28	112.96	94.72	75.52	36.37	20.91	58.35	54.60
C-4	80.92	27.21	53.71	21.73	59.18	10.14	17.07	11.59	42.12
C-5	1066.62	366.74	699.88	1056.29	10.33	365.54	1.19	690.75	9.14
AC-2	253.34	216.93	36.42	15.32	238.03	12.48	204.45	2.84	33.58
AC-3	120.58	98.49	22.09	79.53	41.05	65.13	33.35	14.39	7.70
HX-2	2579.98	1457.42	1122.55	2578.24	1.74	1456.55	0.87	1121.69	0.87
HX-5	3733.58	2673.81	1059.77	3729.44	4.13	2670.84	2.97	1058.61	1.16
MFC process									
C-1	898.85	318.82	580.03	687.19	211.67	236.96	81.86	450.23	129.80
C-3	187.45	61.08	126.37	184.08	3.38	60.12	0.958	123.95	2.42
C-4	221.85	74.86	146.99	177.07	44.77	60.08	14.78	117.00	29.99
C-6	151.21	49.83	101.39	48.07	103.15	20.11	29.72	27.96	73.43
C-7	334.22	114.77	219.45	283.66	50.55	98.10	16.67	185.56	33.89
AC-1	20.14	8.76	11.38	8.58	11.56	3.67	5.08	4.91	6.48
HX-1	1801.63	1471.97	329.67	965.26	836.37	788.17	683.80	177.09	152.58
HX-2	2753.62	2271.54	482.08	2623.81	129.80	2188.93	82.61	434.88	47.19
HX-3	2943.66	2710.37	233.29	1896.73	1046.93	1769.16	941.21	127.57	105.72
DMR process									
C-1	328.51	113.74	214.77	309.63	18.87	108.53	5.21	201.10	13.67
C-2	224.84	76.24	148.60	196.46	28.38	68.94	7.29	127.51	21.08
C-3	1257.09	450.46	806.63	1117.41	139.67	406.89	43.57	710.52	96.11
HX-1	2025.76	1712.66	313.10	1280.48	745.28	1031.25	681.40	249.22	63.88
HX-2	2277.47	1718.89	558.58	1335.89	941.58	1028.54	690.35	307.36	251.22
HX-3	9823.81	5462.66	4361.15	8550.92	1272.89	4596.00	866.66	3954.92	406.23

Table 13. Advanced investment costs rates of process

Component	$\dot{Z}_k$ (\$/h)	$\dot{Z}_k^{UN}$ (\$/h)	$\dot{Z}_k^{AV}$ (\$/h)	$\dot{Z}_k^{EN}$ (\$/h)	$\dot{Z}_k^{EX}$ (\$/h)	$\dot{Z}_k^{UN,EN}$ (\$/h)	$\dot{Z}_k^{UN,EX}$ (\$/h)	$\dot{Z}_k^{AV,EN}$ (\$/h)	$\dot{Z}_k^{AV,EX}$ (\$/h)
C3MR process									
C-1	82.75	74.13	8.62	79.37	3.38	71.10	3.03	8.27	0.35
C-2	187.20	167.19	20.01	118.86	68.34	106.16	61.03	12.70	7.30
C-4	91.60	81.80	9.80	34.14	57.46	30.49	51.31	3.65	6.15
C-5	670.52	599.01	71.52	668.34	2.18	597.06	1.95	71.28	0.23
AC-2	148.75	148.74	0.0076	8.55	140.20	8.55	140.19	0.00044	0.0072
AC-3	148.75	148.746	0.0048	98.37	50.38	98.37	50.38	0.003188	0.0016
HX-2	11.79	7.17	4.62	11.79	0.0071	7.17	0.0043	4.62	0.0028
HX-5	14.87	11.01	3.86	14.85	0.016	11.00	0.012	3.85	0.0043
MFC process									
C-1	715.14	659.10	56.04	695.58	19.56	641.07	18.03	54.51	1.53
C-3	234.60	194.12	40.47	230.40	4.20	190.65	3.48	39.75	0.725
C-4	275.42	246.25	29.18	244.86	30.56	218.92	27.32	25.94	3.24
C-6	221.05	160.44	60.61	207.95	13.09	150.93	9.50	57.02	3.59
C-7	390.73	339.11	51.62	364.11	26.63	316.01	23.11	48.10	3.52
AC-1	185.57	185.21	0.355	139.10	46.47	138.83	46.38	0.266	0.0889
HX-1	19.65	18.48	1.17	10.45	9.21	9.82	8.66	0.623	0.549
HX-2	25.58	24.67	0.914	24.43	1.15	23.56	1.11	0.873	0.0412
HX-3	10.02	8.12	1.90	6.24	3.78	5.05	3.07	1.19	0.719
DMR process									
C-1	266.72	245.79	20.93	254.51	12.21	234.54	11.25	19.97	0.958
C-2	280.73	252.61	28.13	253.87	26.86	228.44	24.17	25.44	2.69
C-3	905.96	843.17	62.78	818.33	87.62	761.62	81.55	56.71	6.07
HX-1	33.04	26.48	6.56	19.90	13.15	15.95	10.54	3.95	2.61
HX-2	34.85	27.33	7.52	20.85	14.00	16.35	10.98	4.50	3.02
HX-3	20.64	11.21	9.42	17.36	3.27	9.44	1.78	7.93	1.49

Table 14. Results Comparison for conventional and advanced exergy and exergoeconomic analyses

Component	Conventional			Advanced		
	ϵ (%)	f (%)	$\dot{C}_{\text{tot}}$ (\$/h)	$\epsilon_{\text{modified}}$ (%)	$f^{\text{AV,EN}}$ (%)	$\dot{C}_{\text{tot}}^{\text{AV,EN}}$ (\$/h)
C3MR process						
C-1	74.14	63.73	129.84	82.06	21.88	37.78
C-2	74.94	52.37	357.44	89.72	17.88	71.06
C-4	62.28	53.10	172.52	92.02	23.95	15.25
C-5	79.95	38.60	1737.15	86.03	9.35	762.03
AC-2	95.67	36.99	402.09	99.95	0.0155	2.84
AC-3	98.13	55.23	269.33	99.77	0.0221	14.40
HX-2	57.12	0.46	2591.77	75.39	0.410	1126.31
HX-5	82.73	0.40	3748.45	94.41	0.362	1062.46
MFC process						
C-1	78.24	44.31	1613.99	87.78	10.80	504.73
C-3	72.61	55.59	422.05	80.04	24.28	163.70
C-4	74.98	55.39	497.27	85.03	18.15	142.94
C-6	75.68	59.38	372.26	94.39	67.10	84.98
C-7	78.56	53.90	724.95	86.84	20.59	233.66
AC-1	99.66	90.21	205.71	99.92	5.14	5.18
HX-1	56.90	1.08	1821.28	93.07	0.351	177.71
HX-2	82.92	0.920	2779.20	96.85	0.200	435.76
HX-3	82.51	0.339	2953.68	99.09	0.920	128.76
DMR process						
C-1	78.56	44.81	595.22	85.69	9.03	221.07
C-2	75.73	55.53	505.57	84.62	16.63	152.95
C-3	79.49	41.88	2163.04	87.27	7.39	767.23
HX-1	43.93	1.60	2058.80	86.43	1.56	253.17
HX-2	87.37	1.51	2312.32	98.09	1.44	311.86
HX-3	78.30	0.210	9844.45	89.96	0.200	3962.85

Table.15. Diverse strategies for dropping exergy destruction avoidable cost

Component	Cost of exergy destruction categories (\$/h)				The part should be focused	Possible strategies to reduce cost of exergy destruction		
	$\dot{C}_D$	$\dot{C}_{D,K}^{AV}$	$\dot{C}_{D,K}^{AV,EN}$	$\dot{C}_{D,K}^{AV,EX}$		Strategy Aa	Strategy Bb	Strategy Cc
C3MR process								
C-1	47.09	31.23	29.51	1.71	EN.	*		
C-2	170.24	112.96	58.35	54.60	EN./EX.	*	*	*
C-4	80.92	53.71	11.59	42.12	EN./EX.		*	*
C-5	1066.62	699.88	690.75	9.14	EN.	*		
AC-2	253.34	36.42	2.84	33.58	EN./EX.		*	*
AC-3	120.58	22.09	14.39	7.70	EN./EX.	*	*	
HX-2	2579.98	1122.55	1121.69	0.87	EN.	*		
HX-5	3733.58	1059.77	1058.61	1.16	EN.	*		
MFC process								
C-1	898.85	687.19	450.23	129.80	EN./EX.	*	*	*
C-3	187.45	184.08	123.95	2.42	EN.	*		
C-4	221.85	177.07	117.00	29.99	EN.	*		
C-6	151.21	48.07	27.96	73.43	EN./EX.		*	*
C-7	334.22	283.66	185.56	33.89	EN.	*		
AC-1	20.14	11.38	4.91	6.48	EN./EX.	*	*	
HX-1	1801.63	329.67	177.09	152.58	EN./EX.	*	*	*
HX-2	2753.62	482.08	434.88	47.19	EN.	*		
HX-3	2943.66	233.29	127.57	105.72	EN./EX.	*	*	*
DMR process								
C-1	328.51	214.77	201.10	13.67	EN.	*		
C-2	224.84	148.60	127.51	21.08	EN.	*		
C-3	1257.09	806.63	710.52	96.11	EN./EX.	*	*	
HX-1	2025.76	313.10	249.22	63.88	EN./EX.	*	*	
HX-2	2277.47	558.58	307.36	251.22	EN./EX.	*	*	*
HX-3	9823.81	4361.15	3954.92	406.23	EN./EX.	*	*	*

a Strategy A: Improving the efficiency of the kth equipment or replacing the equipment with efficient devices.

b Strategy B: Improving the efficiency of the remaining equipment.

c Strategy C: Structural optimization of the overall system

Nomenclature

e	Specific flow exergy (kJ/kg mole)
Ex	Exergy (kW)
$\dot{E}$	Exergy rate (kW)
$\dot{m}$	Mass flow rate (kg mole/s)
h	Enthalpy (kJ/ kg mole)
P	Pressure (kPa)
T	Temperature (°C)
W	Work (kW)
s	Entropy (kJ/ kg mole.°C)
ε	Efficiency (%)
C	Cost rate (\$/h)
c	Unit average exergy cost (\$/Gj)
r	Relative cost difference (%)
f	Exergoeconomic factor (%)
Z	Investment cost (\$)

Subscripts

C	Cold
H	Hot
Tot	Total
D	Destruction
p	Product
F	Fuel
k	kth equipment

Superscript

ph	Physical
ch	Chemical
AV	Avoidable
UN	Unavoidable
EN	Endogenous
EX	Exogenous

Abbreviations

$APCI$	Air Products and Chemicals, Inc.
$C3MR$	Propane precooling
DMR	Dual mixed refrigerant
LNG	Liquefied natural gas
MFC	Mixed fluid cascade
NGL	Natural gas liquids
NG	Natural gas
NRU	Nitrogen Rejection Unit
NLP	Non-Linear Programming
PSO	Particle Swarm Optimization
SMR	Single Mixed Refrigerant

Names Used for Blocks in Plants

C_i	Compressor
Ex_i	Turbo expander
T_i	Tower
HX_i	Multi stream heat exchanger
Di	Flash drum
Vi	Valve
AC_i	Air cooler

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