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Advanced exergetic analysis of five natural gas liquefaction processes

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ABSTRACT

Conventional exergy analysis cannot identify portion of inefficiencies which can be avoided. Also this analysis does not have ability to calculate a portion of exergy destruction which has been produced through performance of a component alone. In this study advanced exergetic analysis was performed for five mixed refrigerant LNG processes and four parts of irreversibility (avoidable/unavoidable) and (endogenous/exogenous) were calculated for the components with high inefficiencies. The results showed that portion of endogenous exergy destruction in the components is higher than the exogenous one. In fact interactions among the components do not affect the inefficiencies significantly. Also this analysis showed that structural optimization cannot be useful to decrease the overall process irreversibilities. In compressors high portion of the exergy destruction is related to the avoidable one, thus they have high potential to improve. But in multi stream heat exchangers and air coolers, unavoidable inefficiencies were higher than the other parts. Advanced exergetic analysis can identify the potentials and strategies to improve thermodynamic performance of energy intensive processes.

1. Introduction

Liquefaction processes such as LNG production consume high amount of energy and any thermodynamic analysis in order to improve their energy efficiency seems to be useful. Exergy analysis pinpoints components and processes with high irreversibilities [1]. Determining part of the irreversibility which can be avoided makes understanding about the process deeper and more applicable. In advanced exergetic analysis irreversibility of a component is divided regarding to two different viewpoints. From the first point of view, exergy destruction is divided into two parts. The first part depends on the inefficiencies of the considered component while the second part depends on the system structure and inefficiencies of the other components of the system. From the other point of view, the exergy destruction is divided into two parts: avoidable part which can be avoided and unavoidable part which cannot be accessible because of the technical and economical limitations. The exogenous and endogenous parts can be further split into avoidable and unavoidable parts. Such segmentation facilitates understanding of the component interconnections and estimation of the potential for improvement [1]. By applying this analysis on the energy intensive processes, their potential for improvement will be identified and optimizations strategies can be developed. In recent years advanced exergetic analysis was carried out on many energy conversion systems. A combined cycle power plant was analyzed by conventional and advanced exergy analyses based on the thermodynamic approach [1]. According to the results, it was determined that most of the exergy destruction of the components was unavoidable. High levels of endogenous exergy destruction show that interaction between the components cannot have significant role in thermodynamic inefficiencies. Tsatsaronis and Morosuk [2] used advanced exergy analysis in order to analyze a vaporization liquefied natural gas and power plant system. The results showed that the endogenous exergy destruction for all components were greater than the exogenous part. Advanced exergetic evaluation of refrigeration machines using different working fluids was carried out in [3]. The results demonstrated effect of the different material properties on the results of advanced exergy analysis. The advanced exergy analysis was studied on a LNG-based cogeneration system [4], a supercritical coal-fired power plant [5] and a refrigeration machine using a Voorhees' compression process [6]. In all of the recent studies the thermodynamic method was used because the working fluid in all of the processes was pure. In [7] a simple cascade refrigeration system for liquefaction of natural gas was investigated by advanced exergetic analysis method. A detail study about the analysis was presented in [8–10]. There are some other papers about the splitting exergy destruction in different plants [11–15]. In [16], a gas engine heat pump (GEHP) drying system was analyzed using both conventional and advanced exergy analyses. For each component, avoidable and unavoidable exergy destructions, modified exergy efficiency values and modified exergy destruction ratios were determined and results showed most of the exergy destructions in the system components were avoidable and these avoidable parts can

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Nomenclature

I	irreversibility (kW)
e	specific flow exergy (kJ/kgmole)
Ex	exergy (kW)
$\dot{E}$	exergy flow (kW)
S	entropy (kJ/kgmole °C)
$\dot{m}$	flow rate (kgmole/s)
Q	heat duty (kW)
W	work transfer rate (kW)
m	number of cold streams
n	number of hot streams

Greek letters

ε	exergy efficiency
Δ	gradient

Subscripts

i	inlet
i	component
o	outlet
sh	shaft
a	air
c	cold
h	hot
k	kth component
D	destruction
P	production
F	fuel
L	loss
tot	total
$others$	other components

Superscripts

ΔP	pressure component
ΔT	thermal component
AV	avoidable
UN	unavoidable
EN	endogenous
EX	exogenous

Abbreviations

AC	air cooler
APCI	Air Products and Chemicals, Inc.
C	compressor
C3MR	C3 Precooled MR
D	flash drum
DMR	dual mixed refrigerant
E	multi stream heat exchanger
LNG	liquefied natural gas
MFC	Mixed Fluid Cascade
MIX	mixer
MR	mixed refrigerant
NG	natural gas
P	pump
PFHE	plate and fin heat exchanger
SMR	Single Mixed Refrigerant
SWHE	spiral wound heat exchanger
V	expansion valve

be reduced by design improvements. Rocco et al. [17] discussed about traditional and advanced exergy analysis methods briefly and described Extended Exergy Accounting (EEA) method. EEA is a comprehensive exergy-based analytical paradigm for the evaluation of the total equivalent primary resource consumption in a generic system. In [18], a tri-generation cycle with 100 MW power production, 70 MW heat and 9 MW cooling capacity was considered. For this tri-generation cycle, effects of various thermodynamic parameters on the amount of endogenous and exogenous exergy destructions, exergy loss and the amount of fuel consumption, were investigated. The results indicate that, increasing compressor pressure ratio, pre-heater outlet temperature and excess air leads to better combustion and lower exergy loss and fuel consumption. Soltani et al. [19] performed an advanced exergy analysis on externally-fired combined-cycle power plant integrated with a biomass gasification unit. Valero et al. [20–23] developed a method called structural theory which presents splitting of irreversibilities from different points of view. Kelly et al. [24,25] presented the bases of engineering method which is explained in Section 4.2.2. This method is especially suitable for the processes that the ideal operation data of their devices is not available. Mixed refrigerant processes for production of LNG have not been analyzed by advanced exergetic method up to now. One important reason is lack of the cycle's ideal data. In this study advanced exergy analysis was carried out on five of the most conventional LNG processes. A new method (engineering or graph) was used for carrying out this analysis. The purpose of this study is identifying the most inefficient components in the liquefaction processes and determination of a part of these inefficiencies which can be avoided. The selected LNG processes have one to three separated cycles and the working fluid in the cycles, except precooling cycle in C3MR process, are mixed refrigerant. Results of these analyses can be a suitable base for structural and operational optimization.

2. Process description

Conventional and advanced exergetic analyses were done on five LNG processes. The Single Mixed Refrigerant processes (SMR) include one mixed refrigerant cycle, thus, number of their equipment and therefore fixed costs are less than the other processes. Moreover, diminishing the process equipment reduces the complexity of it and makes the analysis easier. Process flow diagram of SMR process Linde AG [26] was illustrated in Fig. 1. Four multi stream heat exchangers were used in this process. E-1 and E-2 were used for precooling the natural gas and the other heat exchangers, E-3 and E-4, were used for sub cooling and liquefaction.

The Air Products and Chemicals, Inc. (APCI), in one of their patents [27] introduced a simple and new single stage mixed refrigerant (SMR) process which had less equipment with lower energy consumption compared to the Linde process. Process flow diagram of this process was illustrated in Fig. 2. As this figure shows, only two heat exchangers were used in this process which decreases the fixed costs and complexity of the process. The C3MR process uses two refrigeration cycles: a pure propane cycle for precooling and a mixed refrigerant cycle for liquefaction and subcooling. Using a pure propane cycle improves both production capacity and process efficiency.

The most widely used and successful process for LNG production is propane precooled mixed refrigerant (C3MR) process of APCI. Fig. 3 shows the process flow diagram of Linde process [26]. As can be seen, this process is complicated and has large

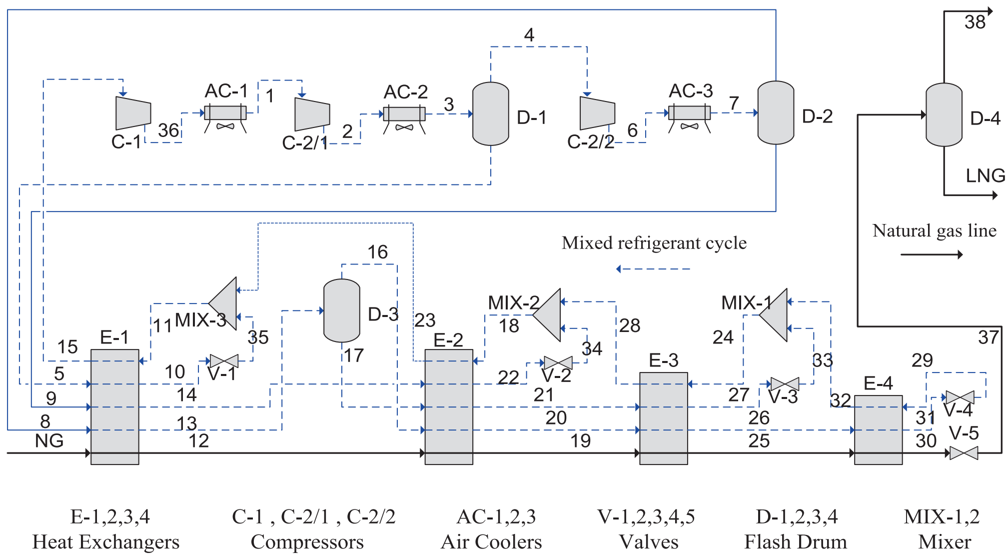

Fig. 1. Process flow diagram of SMR-Linde process.

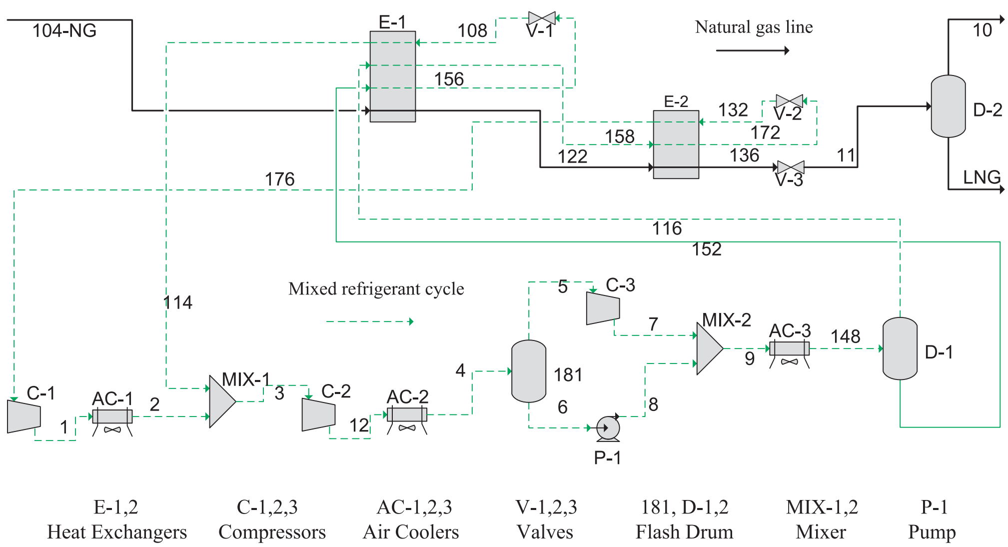

Fig. 2. Process flow diagram of SMR-APCI process.

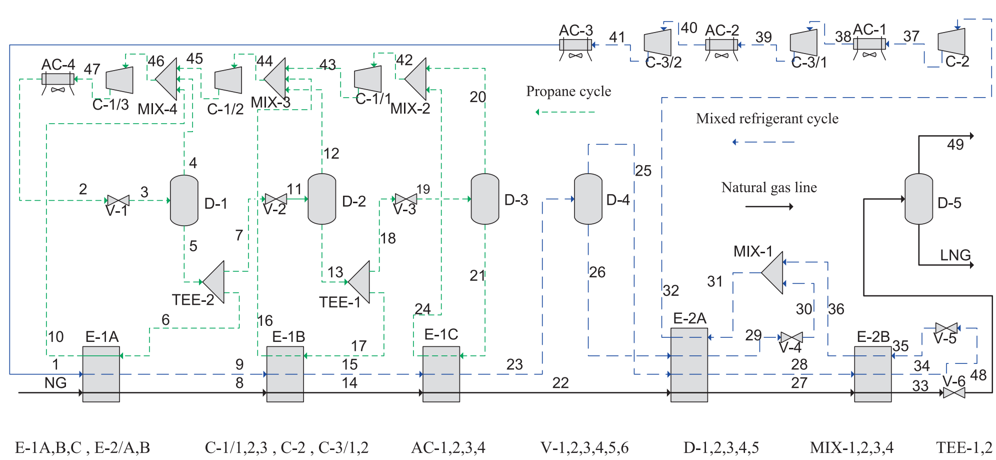

Fig. 3. Process flow diagram of C3MR-Linde process.

equipments; however because of its high efficiency it is economically profitable. This process uses five multi stream heat exchangers. The first three exchangers were used in propane cycle for precooling and the next two ones were used in liquefaction and subcooling cycle.

The double mixed refrigerant (DMR) process which was designed by Shell Company for first time is proper in terms of production capacity and simplicity of the configuration. APCI in another patent [28] introduced a double stage mixed refrigerant process which has high efficiency in addition of simplicity. Fig. 4 shows the process flow diagram. This process uses two multi stream heat exchangers for precooling the first mixed refrigerant cycle and two others for liquefaction and subcooling.

Number of refrigeration cycles is one of the most determining factors in liquefaction processes. Increasing number of the cycles increases the process efficiency and capacity and decreases the operating costs. But this point increases number of the components and consequently fixed costs. Economically, the best situation occurs when capacity of the process can be increased via applying process design procedures (which improve the thermodynamic efficiency) without increasing number of the cycles and components. The Linde AG and Stat oil, introduced a new LNG process which has three refrigeration cycles and high capacity called Mixed Fluid Cascade (MFC) [26]. Energy efficiency of this process is high because it uses three different mixed refrigerants in each cycle. This point result a decrease and increase in operating costs and fixed costs respectively. Process flow diagram of MFC was illustrated in Fig. 5. As can be seen, in this configuration two multi stream heat exchangers were used in the first mixed refrigerant cycle for precooling the feed. The other heat exchangers were used in the second and third cycles for liquefaction and subcooling [26].

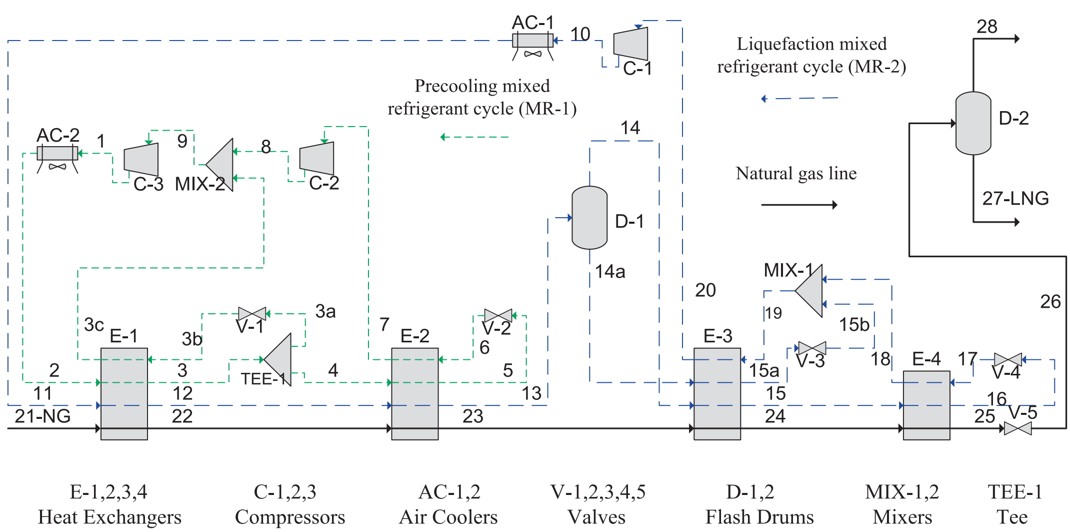

Fig. 4. Process flow diagram of DMR-APCI process.

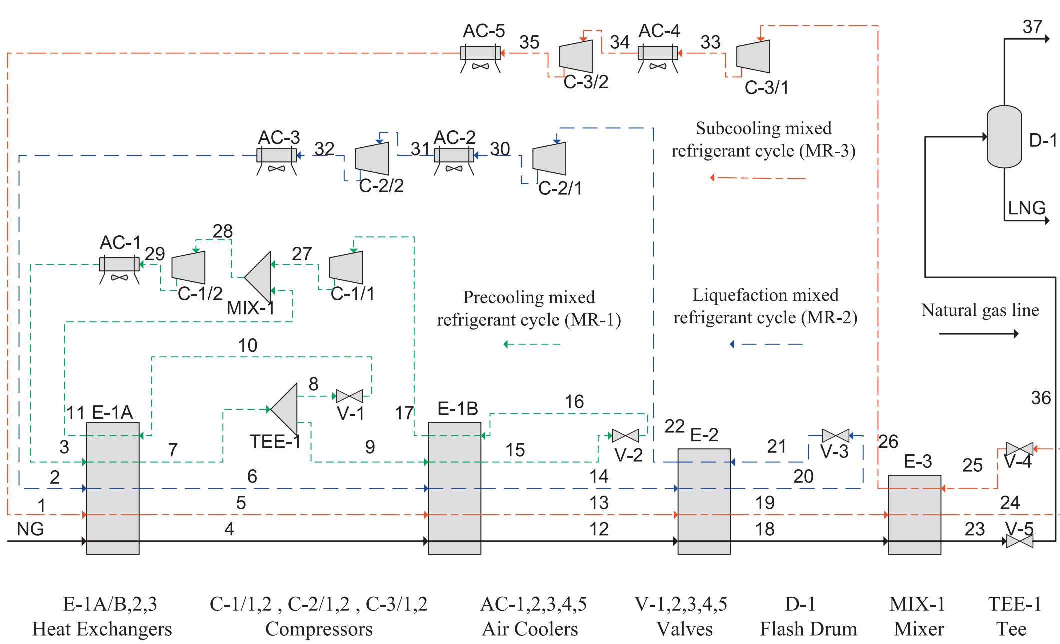

Fig. 5. Process flow diagram of MFC-Linde process.

3. Numerical implementation

3.1. Processes simulation

Process simulation is a widely used technique in the design, analysis, and optimization of chemical processes. Simulators are computer programs that simulate behavior of the process plants using appropriate mathematical models. Simulators are used for various purposes [29]:

- to perform material balance and energy balance of processes,
- to determine the detailed specifications of all units of a process,
- to troubleshoot startup and shut-down operations,
- to determine performance under off-design conditions,
- to design and troubleshoot control strategies.

Simulators are also extremely useful teaching tools to understand behavior of the individual units as well as interconnected units, namely a complete plant. Cryogenic processes differ somewhat from general chemical processes [29]. Some of the features special to cryogenic processes include multi stream heat exchangers, low temperature and high operational pressure. In order to perform thermodynamic calculations and the processes simulation an equation (EOS) of state is required.

In natural gas liquefactions processes the allowable impurity levels in a gas to be liquefied are much lower than that of a pipeline-quality gas. So the related ESOs can predict the physical properties with high accuracy. In fact the more similar the character of the mixture molecules, the more orderly their behavior. Based on the mixtures discussed in this study and based on the feed composition it can be said that the simulators can estimate thermodynamic properties with good accuracy.

In this study EOS was selected based on the published records in this area. In [30], a C3MR process was considered and PRSV equation of state was used for calculation of the physical properties. Also Mehrpooya et al. [31] analyzed a NGL process and used PRSV equation of state. Generally cubic equations of states such as Peng–Robinson or Soave–Redlich–Kwong, and higher order equations like PRSV are useful for simulating the natural gas processes. In this paper the processes were simulated by Aspen HYSYS software with PRSV thermodynamic model.

Table 1
Feed gas and refrigerant specifications of SMR-Linde process.

Stream name	NG Natural gas feed	LNG Liquid product	1 Mixed refrigerant
Flow (kmol/h)	25120.00	24065.97	61800.00
Temperature (°C)	13.00	−164.00	35.00
Pressure (bar)	60.00	1.01	9.00
Enthalpy (kJ/kmol)	−77092.15	−92050.69	−85297.06
Components (mol%)			
CH_4	89	89.64	27.4
C_2H_6	5.5	5.74	33.4
C_3H_8	2.5	2.61	25.8
n-C_4H_{10}	1	1.04	7.7
N_2	2	0.97	5.7

Table 2
Feed gas and refrigerant specifications of SMR-APCI process.

Stream name	104-NG Natural gas feed	LNG Liquid product	148 Mixed refrigerant
Flow (kmol/h)	27054.37	25011.22	67900.00
Temperature (°C)	30.00	−162.10	32.00
Pressure (bar)	66.51	1.01	60.00
Enthalpy (kJ/kmol)	−76456.32	−91277.69	−92501.93
Components (mol%)			
CH_4	94.46	94.73	27.4
C_2H_6	2.61	2.82	33.4
C_3H_8	0.65	0.7	25.8
i-C_4H_{10}	0.65	0.7	0
n-C_4H_{10}	0.65	0.7	7.7
N_2	0.98	0.33	5.7

3.2. Simulations validating

Five most conventional and classic LNG processes were studied in this paper. They were simulated by operating data (pressure, temperature, composition and molar flow of the process streams) and their configurations, next simulations were investigated in order to validate the results through some indexes such as operating conditions in different parts of the process, specific power consumption (kW h/kg produced LNG), performance of the multi stream heat exchangers and behavior of mixed refrigerants in temperature–entropy and pressure–enthalpy diagrams. It should be noted that in order to reaching the real specific power consumption in simulations, the process must be simulated with high accuracy otherwise the resulted specific power consumption will differ very much from its real value. In this study the results showed that all processes were simulated with appropriate accuracy, thus results of the exergetic and advanced exergetic analyses can be reliable and useful. In [26], operating conditions of feed gas for three processes of Linde AG were presented. In [27,28] there is more detail information about the APCI processes. In Tables 1–6 and Figs. 6–10, the required data about the considered processes were presented according to the references and simulations.

3.3. Thermodynamic data calculation

In this study the main thermodynamic data including operating condition and exergy value of streams were calculated by means of

Table 3
Feed gas and refrigerant specifications of C3MR-Linde process.

Stream name	NG Natural gas feed	LNG Liquid product	1 Mixed refrigerant	2 Propane
Flow (kmol/h)	25120.00	24065.97	33590.00	32000.00
Temperature (°C)	13.00	−164.00	35.00	35.00
Pressure (bar)	60.00	1.01	49.00	14.30
Enthalpy (kJ/kmol)	−77092.15	−92050.69	−80603.59	−118735.37
Components (mol%)				
CH_4	89	89.64	41.8	0
C_2H_6	5.5	5.74	29.9	0
C_3H_8	2.5	2.61	21.3	100
n-C_4H_{10}	1	1.04	0	0
N_2	2	0. 97	7	0

Table 4
Feed gas and refrigerant specifications of DMR-APCI process.

Stream name	21-NG Natural gas feed	27-LNG Liquid product	11 Mixed refrigerant	2 Mixed refrigerant
Flow (kmol/h)	18849.60	17561.45	25200.00	23007.60
Temperature (°C)	26.85	−166.00	31.85	36.85
Pressure (bar)	65.00	1.01	48.60	19.20
Enthalpy (kJ/kmol)	−74878.10	−91535.68	−80803.00	−115394.20
Components (mol%)				
CH_4	87.5	89.31	41.8	0
C_2H_6	5.5	5.9	29.9	24.82
C_3H_8	2.1	2.25	21.3	64.15
n-C_4H_{10}	0.5	0.54	0	11.03
i-C_4H_{10}	0.3	0.32	0	0
i-C_5H_{12}	0.1	0.12	0	0
N_2	4	1.56	7	0

Table 5
Feed gas and refrigerant specifications of MFC-Linde process.

Stream name	NG Natural gas feed	LNG Liquid product	1 Mixed refrigerant	2 Mixed refrigerant	3 Mixed refrigerant
Flow (kmol/h)	25120.00	24197.52	18100.00	25700.00	34390.00
Temperature (°C)	13.00	−164.30	35.00	35.00	35.00
Pressure (bar)	60.00	1.01	33.90	27.90	16.90
Enthalpy (kJ/kmol)	−77092.15	−91988.42	−11165.24	−51906.13	−104423.47
Components (mol%)					
CH_4	89	89.62	42.45	12.65	0
C_2H_6	5.5	5.71	0	32.92	0.01
C_2H_4	0	0	40.24	27.77	11.29
C_3H_8	2.5	2.6	0	26.66	73.57
n-C_4H_{10}	1	1.04	0	0	15.13
N_2	2	1.03	17.31	0	0

Table 6
Specific power consumption (SPC) for LNG processes.

SPC (kW h/kg LNG)	Simulation	Real case [36]
SMR-Linde	0.3572	0.3 < SPC < 0.4
SMR-APCI	0.3046	0.3 < SPC < 0.4
C3MR-Linde	0.2711	SPC < 0.3
DMR-APCI	0.2746	SPC < 0.3
MFC-Linde	0.2545	SPC < 0.3

chemical process simulator and Matlab software. Exergy analysis calculations were done in two steps: calculation of streams exergy and writing exergy balance around each device in order to obtain irreversibility and exergy efficiency.

4. Conventional exergetic analysis

In conventional exergy analysis, irreversibilities within each component of a plant are identified. In addition, performance of the devices is determined through calculation of exergy efficiency of the equipment. In a system the parameters that are used for conventional exergetic evaluation are: (1) rate of exergy destruction or irreversibility which is calculated by writing the exergy balance around each component, (2) energetic efficiency which is formulated separately for different equipments. Exergy balance around the control volume is written as below [31]:

$$Ex_i + Ex_{Qi} = Ex_o + Ex_{Qo} + W_{sh} + I \quad (1)$$

where Ex_i, Ex_o = Exergy of inlet and outlet material streams respectively. Ex_{Qi} and Ex_{Qo} = Exergy of inlet and outlet energy streams respectively. W_{sh} = Shaft work. I = Irreversibility or exergy destruction.

The exergetic efficiency (or second law efficiency) of various steady flow devices can be determined from its general definition, ε = (Exergy recovered)/(Exergy supplied) [32]. A comparison of exergy efficiency definitions with focus on low temperature processes was carried out by Marmolejo-Correa and Gundersen [33]. They compared two classes of exergy efficiency definitions and

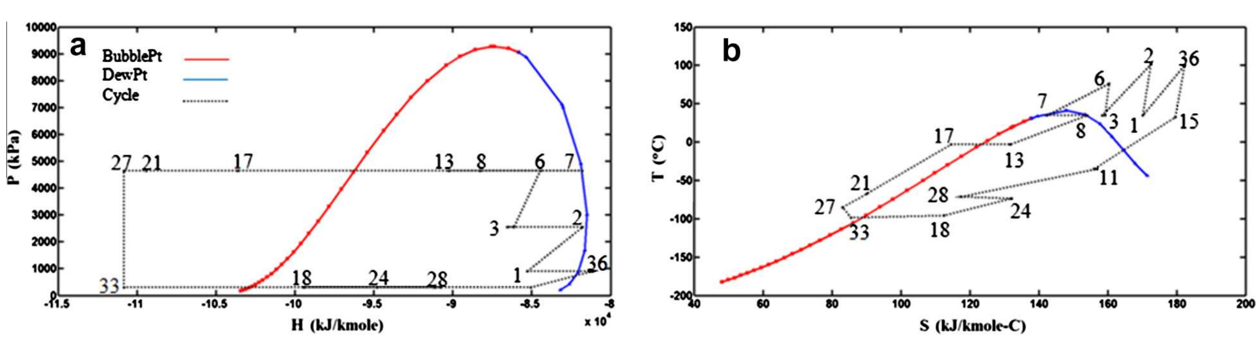

Fig. 6. *P–H* and *T–S* diagrams of the SMR-Linde process.

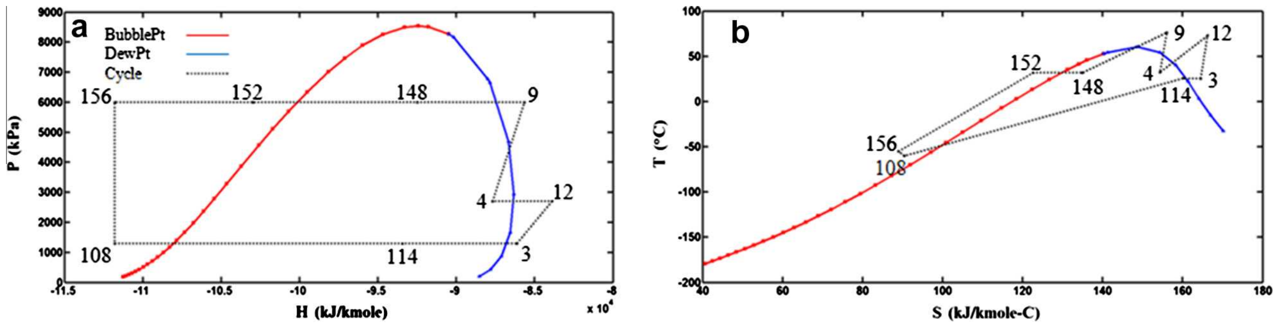

Fig. 7. *P–H* and *T–S* diagrams of the SMR-APCI process.

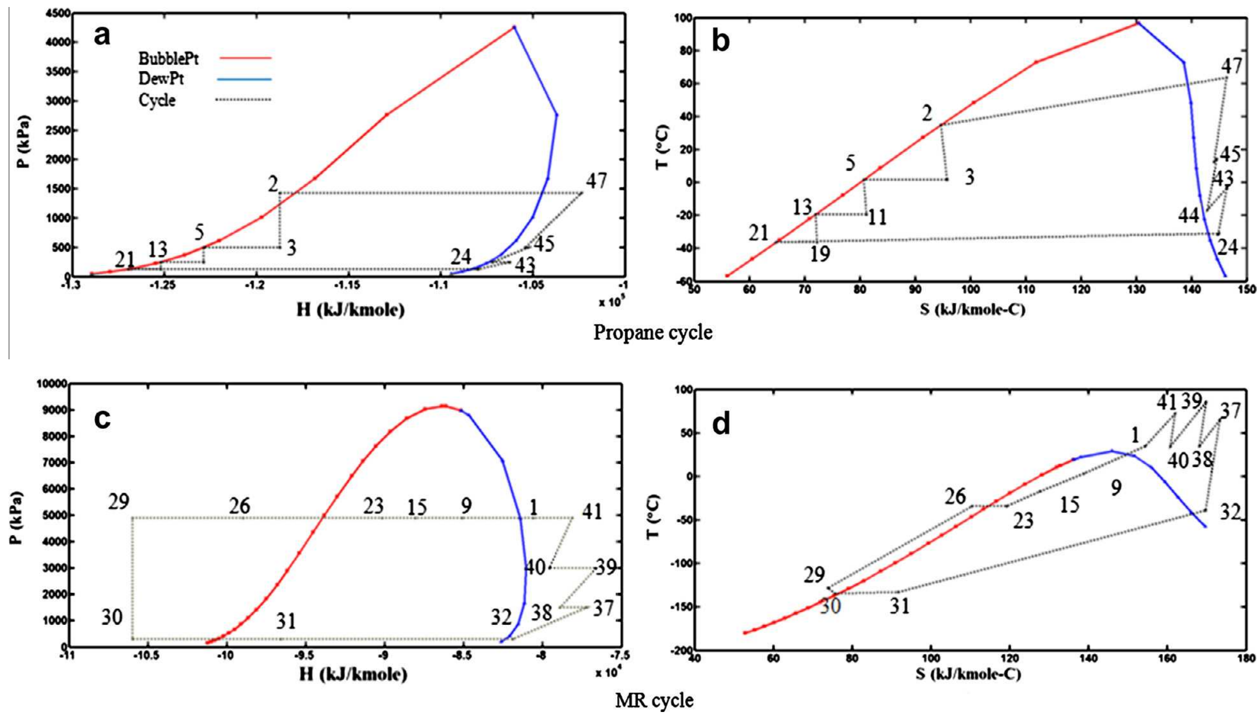

Fig. 8. *P–H* and *T–S* diagrams of the C3MR process (Propane and MR).

applied them on a simple process for liquefaction of natural gas. Mehrpooya et al. [34] illustrated simulation and exergy-method analysis of an industrial refrigeration cycle used in NGL recovery units. Analysis of a NGL plant refrigeration cycle by the exergy method was also presented by Tirandazi et al. [31]. Tables 7–11 summarize the thermodynamic data for the selected material streams of liquefaction processes. Table 12 also shows the definitions for irreversibility and exergetic efficiency of different components. Except the air cooler, all definitions were extracted from [31]. There was not any usable definition about irreversibility and exergy efficiency of this kind of air cooler in the references, so new definitions based on the main concept of exergy efficiency were developed.

5. Advanced exergy analysis

Advanced exergy analysis was performed based on the results of exergy analysis, thus the input data are irreversibilities and exergetic efficiencies of the process components. The main idea of this analysis is categorizing the irreversibility or exergy destruction of the process components. Irreversibility occurring in a device not only depends on its performance, but also is related to the irreversibility of remaining components which have been connected to it. Conventional exergy analysis calculates the irreversibility of the components accurately and easily, however it cannot categorize the irreversibility in terms of origin. Also it cannot calculate a part of irreversibility of a component which is induced from the remaining components of the process.

In advanced exergetic analysis, irreversibility of a device can be divided from two points of view: (1) origin of irreversibility production and (2) removing ability of it. Based on the first point of view, the exergy destruction is divided to two parts:

- Endogenous exergy destruction.
- Exogenous exergy destruction.

The endogenous exergy destruction is due to performance of the under consideration component and it exits even the other components work ideally. The exogenous exergy destruction is caused by the inefficiencies within the remaining components of the overall system. Based on the removing ability, the exergy destruction is divided to two other parts:

- Avoidable exergy destruction.
- Unavoidable exergy destruction.

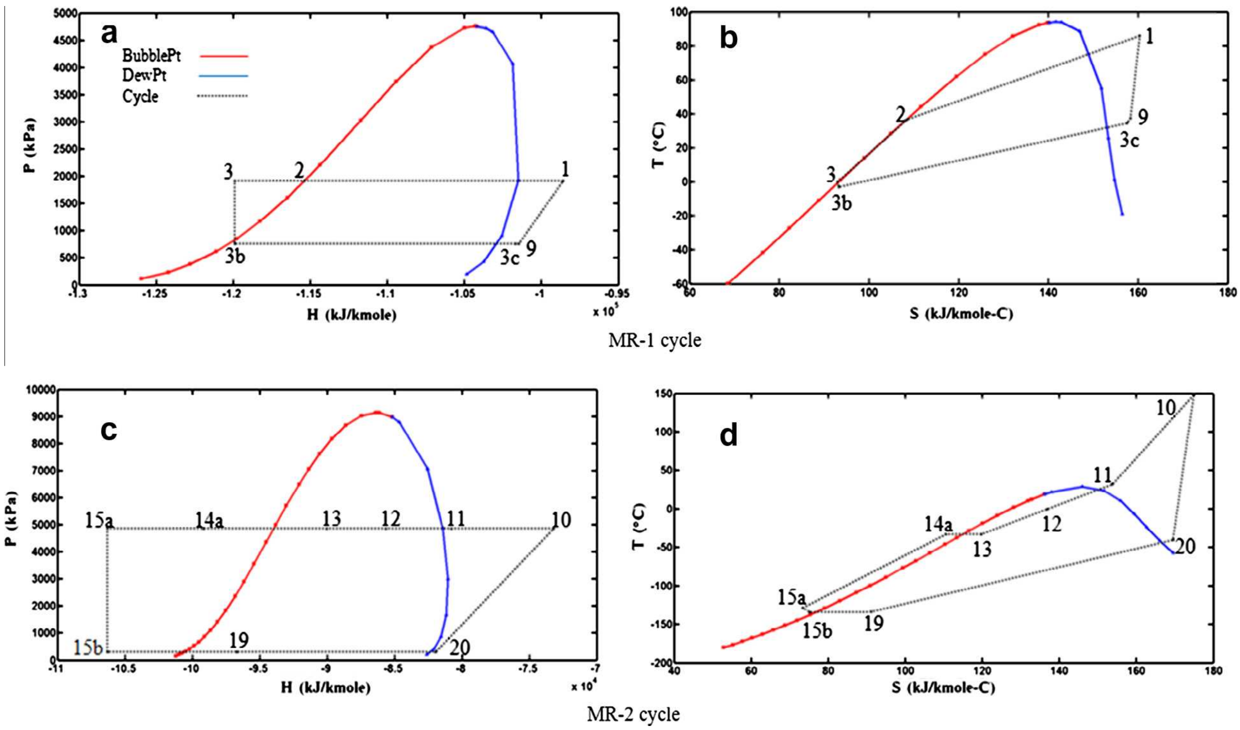

Fig. 9. *P–H* and *T–S* diagrams of the DMR process (MR-1 and MR-2).

The unavoidable part of exergy destruction of the component presents a part which cannot be eliminated, even if the best available technologies are used. While avoidable part can be eliminated through technical improvements of the process equipment. These divisions improve our understanding from the process components and relation among them.

5.1. Avoidable/unavoidable exergy destruction

As discussed, some technical and economical limitation makes a part of irreversibility unavoidable. Thus, total exergy destruction of a component k can be presented as below:

$$\dot{E}_{D,k} = \dot{E}^{AV}_{D,k} + \dot{E}^{UN}_{D,k} \quad (2)$$

Unavoidable condition is assumed based on the knowledge and experience of the analyzer by considering the maximum improvement potential that could be achieved for each plant component in the foreseeable future [1]. It's noteworthy that energy consumption and exergy destruction produced in a device such as compressor is decreased when its efficiency improves and this point will improve performance of the whole system, however replacing a more efficient device increases the capital costs. Thus, efficiency of the components cannot be improved more than a certain extent because of the technical and economical limitations. For example for selecting a cryogenic compressor, upper limit for efficiency can be considered as 90% or 95%. This shows that the compressor produces certain amount of irreversibility because of its non-ideal performance. This part of irreversibility is called unavoidable. Determining the unavoidable exergy destruction depends on the unavoidable conditions assumed by the analyzer [25]. In fact the analyzer assumes the unavoidable conditions based on the process conditions, cost of the process components, previous experiences and information presented in the literature. Assumed unavoidable conditions in this study were listed in Table 13.

In order to decreasing the exergy destruction by improving performance of the compressors, their thermodynamic or isentropic efficiency should be changed. So considered assumption for unavoidable conditions for the compressors is isentropic efficiency of 90%. In the case of heat exchangers, either multi stream heat exchangers or air coolers, thermodynamic performance depends on minimum temperature approach.

Expression $(\dot{E}_D/\dot{E}_P)^{UN}_k$ is used to calculate unavoidable exergy destruction per unit of produced exergy of kth component. This expression is calculated when the best condition is assumed for performance of kth component considering the economical or technical limitations, thus the unavoidable exergy destruction is obtained as below:

$$\dot{E}^{UN}_{D,k} = \dot{E}_{P,k}(\dot{E}_D/\dot{E}_P)^{UN}_k \quad (3)$$

Now the avoidable exergy destruction can be also calculated through Eq. (2).

$\dot{E}_P$ is the produced exergy of each component. In exergy analysis there are two important models for evaluating the exergetic efficiency: Input/output and fuel/product. In the first model exergetic efficiency defined as the ratio of exergy of input streams to exergy of output streams and in the second one, consumed and produced exergy are considered. Morosuk and Tsatsaronis [4], Torres et al. [20] and Valero et al. [22], Marmolejo-Correa et al. [33] and Mehrpooya et al. [35] explained two models and used the fuel/product concept in order to analyze a process. In [33], a natural gas liquefaction process was analyzed from two points of view and the results showed that the fuel/product concept can present more reasonable values. For example, as it has been explained in [22], exergy of input work to the compressor is considered as the fuel and the deference between exergy of input and output streams are considered as the product. In this research the processes were studied by fuel/product model.

5.2. Endogenous/exogenous exergy destruction

A part of exergy destruction produced in a device is related to its thermodynamic performance and always exists even if other

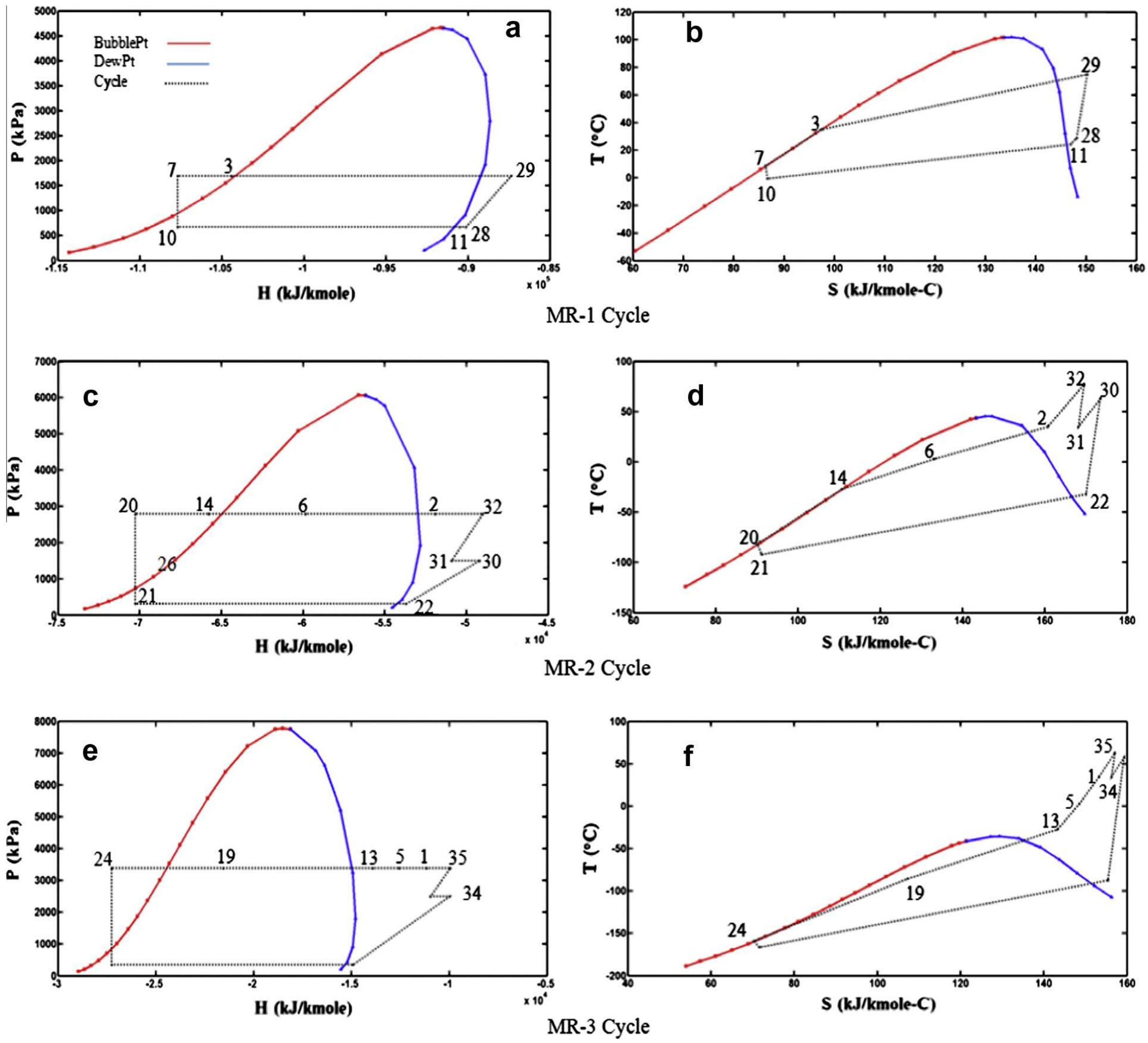

Fig. 10. *P–H* and *T–S* diagrams of the MFC process (MR-1, MR-2 and MR-3).

components work ideally. Accordingly another part is related to the induced destruction from the remaining components, so the total exergy destruction of *k*th component can be presented as below:

$$\dot{E}_{D,k} = \dot{E}^{EN}_{D,k} + \dot{E}^{EX}_{D,k} \tag{4}$$

The results of this division give deeper understanding about the process and interactions among the components. Also based on the results a suitable and accurate structural optimization can be performed on the process. Nonetheless calculation of endogenous exergy destruction for a component is more difficult than unavoidable exergy destruction and this is the main problem of advanced exergy analysis. Accuracy of calculations can directly affects the results of the analysis.

Several different methods were presented to obtain the endogenous exergy destruction. A detail description of the methods can be found in [24,25]. Thermodynamic cycles and Engineering (graphical) methods are two of the main methods which will be explained as below:

5.2.1. Thermodynamic cycles

Real and ideal diagrams of temperature–entropy (*T–S*) for a cycle are used for endogenous exergy destruction calculations. The real *T–S* diagrams show irreversibility of the process components, however in ideal diagrams there are just isentropic and isothermal lines. In this method, a hybrid diagram is drawn for each component, the way that the only under consideration component has non-ideal behavior and remaining components work ideally. In fact *k*th component hybrid diagram is an ideal diagram of the cycle which only irreversibility of *k*th component is applied on. Thus number of the hybrid diagrams must be equal to number of the under consideration components.

The most important advantage of this method is its ability for using in any equipment in the process. Also it can be said that the results are gained with suitable accuracy. Moreover, this method requires the ideal operation of a component [25]. The ideal operation of some components and also ideal diagram of some cycles are not available or can be determined approximately.

Tsatsaronis et al. [1–14] performed advanced exergetic analysis on the large number of power cycles based on this method. Working fluids in these cycles were pure and ideal data of them were available. In the case of mixed refrigerant processes ideal operation of the components and ideal diagrams of the cycles are not available because the mixed refrigerant does not evaporate at a constant temperature thus the method cannot be applied.

Table 7
Thermodynamic data for SMR-Linde process material streams.

Stream no.	Temperature (°C)	Pressure (bar)	Flow (kmol/h)	Physical exergy (kW)	Chemical exergy (kW)	Total exergy (kW)
NG	13.00	60.00	25120.00	68042.09	6338117.01	6406159.10
1	35.00	9.00	61800.00	90277.35	25806953.25	25897230.60
2	101.60	25.50	61800.00	138283.92	25806953.25	25945237.17
3	35.00	25.50	61800.00	128323.00	25806953.25	25935276.25
4	35.00	25.50	60992.92	126845.98	25324428.98	25451274.97
5	35.00	25.50	807.08	1219.27	482782.01	484001.29
6	76.51	46.50	60992.92	148967.33	25324428.98	25473396.31
7	35.00	46.50	60992.92	141178.78	25324428.98	25465607.76
8	35.00	46.50	41428.57	100407.31	15215221.65	15315628.96
9	35.00	46.50	19564.35	37867.58	10112111.22	10149978.81
10	−1.00	25.50	807.08	1245.98	482782.01	484027.99
11	−34.89	3.00	61800.00	61232.31	25806953.25	25868185.57
12	−3.00	60.00	25120.00	68444.33	6338117.01	6406561.34
13	−3.00	46.50	41428.57	102604.36	15215221.65	15317826.02
14	−3.00	46.50	19564.38	38591.07	10112111.22	10150702.30
15	32.69	3.00	61800.00	45590.91	25806953.25	25852544.17
16	−3.00	46.50	20673.81	52415.88	5801094.53	5853510.41
17	−3.00	46.50	20754.76	46689.84	9417625.76	9464315.61
18	−70.90	3.00	60992.92	111326.39	25324428.98	25435755.37
19	−67.00	60.00	25120.00	81867.52	6338117.01	6419984.53
20	−67.00	46.50	20673.81	64083.17	5801094.53	5865177.70
21	−67.00	46.50	20754.76	55093.38	9417625.76	9472719.15
22	−50.00	46.50	19564.35	43727.96	10112111.22	10155839.18
23	−34.94	3.00	60992.92	59884.18	25324428.98	25384313.16
24	−95.71	3.00	41428.57	93692.09	15215221.65	15308913.74
25	−93.00	60.00	25120.00	91551.00	6338117.01	6429668.02
26	−93.00	46.50	20673.81	73025.33	5801094.53	5874119.86
27	−85.00	46.50	20754.76	59221.04	9417625.76	9476846.80
28	−73.38	3.00	41428.57	69119.34	15215221.65	15284340.99
29	−162.80	3.00	20673.81	92596.49	5801094.53	5893691.02
30	−161.00	60.00	25120.00	121713.17	6338117.01	6459830.19
31	−156.00	46.50	20673.81	95824.51	5801094.53	5896919.04
32	−95.52	3.00	20673.81	35363.57	5801094.53	5836458.10
33	−98.34	3.00	20754.76	55103.40	9417625.76	9472729.17
34	−66.22	3.00	19564.35	39591.00	10112111.22	10151702.22
35	−25.30	3.50	807.08	1122.12	482782.01	483904.13
36	100.20	9.00	61800.00	99047.05	25806953.25	25906000.31
37	−164.00	1.01	25120.00	117732.84	6338117.01	6455849.86
38	−164.00	1.01	1054.03	1051.14	181906.64	182957.78
LNG	−164.00	1.01	24065.97	116248.95	6156643.12	6272892.07

Table 8
Thermodynamic data for SMR-APCI process material streams.

Stream no.	Temperature (°C)	Pressure (bar)	Flow (kmol/h)	Physical exergy (kW)	Chemical exergy (kW)	Total exergy (kW)
1	102.20	13.00	30395.03	55989.86	10437211.77	10493201.63
2	32.00	13.00	30395.03	52004.17	10437211.77	10489215.93
3	25.27	13.00	67900.00	114596.74	28354241.52	28468838.26
4	32.31	27.10	67900.00	142524.89	28354241.52	28496766.41
5	32.31	27.10	62300.00	132063.96	25087802.51	25219866.47
6	32.31	27.10	62300.00	8838.65	3268966.66	3277805.31
7	88.57	60.00	62300.00	162102.51	25087802.51	25249905.02
8	36.37	60.00	5600	9290.47	3268966.66	3278257.13
9	76.27	60.00	67900.00	171669.35	28354241.52	28525910.87
10	−162.10	1.01	2043.16	2029.71	432317.84	434347.55
11	−162.10	1.01	27054.37	122215.71	6609489.36	6731705.07
12	72.62	27.10	67900.00	147566.44	28354241.52	28501807.95
104-NG	30.00	66.51	27054.37	75122.73	6609489.36	6684612.09
108	−60.00	13.01	37504.97	87971.69	17919931.49	18007903.18
114	25.71	13.00	37504.97	62477.95	17919931.49	17982409.43
116	32.00	60.00	30395.03	78082.65	10437211.77	10515294.42
122	−52.50	66.50	27054.37	81267.68	6609489.36	6690757.04
132	−167.00	2.00	30395.03	137584.15	10437211.77	10574795.92
136	−153.80	66.50	27054.37	127108.44	6609489.36	6736597.80
148	32.00	60.00	67900.00	161277.14	28354241.52	28515518.66
152	32.00	60.00	37504.97	80292.75	17919931.49	18000224.24
156	−54.91	60.00	37504.97	92825.02	17919931.49	18012756.51
158	−21.00	60.00	30395.03	82336.24	10437211.77	10519548.01
172	−164.30	60.00	30395.03	144022.22	10437211.77	10581233.99
176	−22.80	1.99	30395.03	15745.87	10437211.77	10452957.64
LNG	−162.10	1.01	25011.22	119905.76	6177451.76	6297357.52

Table 9
Thermodynamic data for C3MR-Linde process material streams.

Stream no.	Temperature (°C)	Pressure (bar)	Flow (kmol/h)	Physical exergy (kW)	Chemical exergy (kW)	Total exergy (kW)
NG	13.00	60.00	25120.00	68042.09	6338117.01	6406159.10
1	35.00	49.00	33590.00	83125.30	11730383.33	11813508.64
2	35.00	14.30	32000.00	46761.02	19228355.56	19275116.58
3	1.63	5.00	32000.00	43761.47	19228355.56	19272117.03
4	1.63	5.00	7963.83	8545.80	4785357.45	4793903.25
5	1.63	5.00	24036.17	35215.66	14442998.11	14478213.77
6	1.63	5.00	9133.74	13381.95	5488339.28	5501721.23
7	1.63	5.00	14902.43	21833.71	8954658.83	8976492.54
8	3.40	60.00	25120.00	68239.60	6338117.01	406356.61
9	3.40	49.00	33590.00	84354.30	11730383.33	11814737.63
10	19.07	5.00	9133.74	9626.79	5488339.28	5497966.07
11	−19.37	2.50	14902.43	21293.34	8954658.83	8975952.16
12	−19.37	2.50	1953.71	1323.29	1173956.78	1175280.06
13	−19.37	2.50	12948.72	19970.05	7780702.05	7800672.10
14	−17.00	60.00	25120.00	69134.76	6338117.01	6407251.77
15	−17.00	49.00	33590.00	87612.91	11730383.33	11817996.24
16	−19.37	2.50	7251.28	5079.64	4357193.15	4362272.79
17	−19.37	2.50	7251.28	11183.23	4357193.15	4368376.38
18	−19.37	2.50	5697.43	8786.82	3423508.90	3432295.72
19	−36.24	1.30	5697.43	8649.98	3423508.90	3432158.88
20	−36.24	1.30	537.03	164.47	322694.66	322859.14
21	−36.24	1.30	5160.40	8485.50	3100814.24	3109299.74
22	−34.00	60.00	25120.00	70697.67	6338117.01	6408814.68
23	−34.00	49.00	33590.00	91620.81	11730383.33	11822004.14
24	−30.81	1.30	5160.40	1457.35	3100814.24	3102271.59
25	−34.00	49.00	9634.72	25824.08	2208404.23	2234228.31
26	−34.00	49.00	23955.28	63152.67	9524623.16	9587775.83
27	−128.00	60.00	25120.00	104733.47	6338117.01	6442850.48
28	−128.00	49.00	9634.72	40083.01	2208404.23	2248487.23
29	−128.00	49.00	23955.28	89315.58	9524623.16	9613938.73
30	−134.10	3.00	23955.28	85670.51	9524623.16	9610293.67
31	−133.00	3.00	33590.00	108249.09	11730383.33	11838632.43
32	−38.84	3.00	33590.00	28272.85	11730383.33	11758656.18
33	−161.00	60.00	25120.00	121713.17	6338117.01	6459830.19
34	−161.00	49.00	9634.72	46739.41	2208404.23	2255143.63
35	−167.10	3.00	9634.72	45359.33	2208404.23	2253763.55
36	−131.50	3.00	9634.72	20086.48	2208404.23	2228490.70
37	65.45	15.00	33590.00	61721.93	11730383.33	11792105.26
38	35.00	15.00	33590.00	60525.77	11730383.33	11790909.10
39	85.66	30.00	33590.00	77393.57	11730383.33	11807776.90
40	35.00	30.00	33590.00	74487.31	11730383.33	11804870.65
41	71.92	49.00	33590.00	85083.88	11730383.33	11815467.21
42	−31.32	1.30	5697.43	1621.17	3423508.90	3425130.07
43	−3.19	2.50	5697.43	3610.26	3423508.90	3427119.17
44	−16.46	2.50	14902.43	9953.98	8954658.83	8964612.81
45	14.54	5.00	14902.43	15747.76	8954658.83	8970406.59
46	12.66	5.00	32000.00	33865.89	19228355.56	19262221.45
47	63.70	14.30	32000.00	54877.36	19228355.56	19283232.91
48	−164.00	1.01	25120.00	117732.84	6338117.01	6455849.86
49	−164.00	1.01	1054.03	1051.14	181906.64	182957.78
LNG	−164.00	1.01	24065.97	116248.95	6156643.12	6272892.07

5.2.2. Engineering (graphical) method

Engineering method and procedure for calculation of the endogenous exergy destruction of kth component was clearly explained in [25]. Also in [24] all methods of advanced exergetic analysis were presented and the advantages and disadvantages of them were investigated. The engineering method is based on the conventional exergetic analysis results and it's an accurate method to analysis of the energy conversion systems. The main principle of this method is calculation of the endogenous exergy destruction of kth component ($\dot{E}^{EN}_{D,k}$) through drawing a diagram such as Fig. 11 based on Eq. (5) which is established for any real energy conversion system (exergy balance):

$$\dot{E}_{F,tot} = \dot{E}_{P,tot} + \dot{E}_{D,tot} + \dot{E}_{L,tot} \tag{5}$$

$$\dot{E}_{D,tot} = \dot{E}_{F,tot} - \dot{E}_{P,tot} - \dot{E}_{L,tot} \tag{6}$$

On the other hand, total exergy destruction is summation of the exergy destructions produced within the components individually:

$$\dot{E}_{D,tot} = \sum_k \dot{E}_{D,k} = \dot{E}_{D,k} + \dot{E}_{D,others} \tag{7}$$

Target device is kth component and other components in the process are remaining components namely "others" ($\dot{E}_{D,others}$). The diagram shows variations of the total irreversibility of the process ($\dot{E}_{D,tot}$) vs. irreversibility of all components except under consideration components ($\dot{E}_{D,others}$), thus intercept of the line will be endogenous exergy destruction ($\dot{E}^{EN}_{D,k}$) in kth component.

Using this method is possible when some detail is considered: (1) Endogenous exergy destruction, according to its definition, is a part of irreversibility that produced due to its performance. Thus this part of exergy destruction is a function of component's exergetic efficiency, so the exergetic efficiency of the kth component must be kept constant ($\varepsilon_k = const$) while $\dot{E}_{D,others}$ is being varied. (2) This diagram is useful when the line is drawn as a straight line not a curve. Kelly et al. [24,25] proved that the line is straight if exergetic efficiency of a component remains constant by varying $\dot{E}_{D,others}$.

Table 10
Thermodynamic data for DMR-APCI process material streams.

Stream no.	Temperature (°C)	Pressure (bar)	Flow (kmol/h)	Physical exergy (kW)	Chemical exergy (kW)	Total exergy (kW)
1	85.98	19.20	23007.60	44907.17	13228352.56	13273259.73
2	36.85	19.20	23007.60	36539.07	13228352.56	13264891.63
3	−0.05	19.20	23007.60	37167.49	13228352.56	13265520.05
3a	−0.05	19.20	13784.40	22267.92	7925420.43	7947688.35
3b	−2.86	7.60	13784.40	21886.02	7925420.43	7947306.45
3c	34.61	7.60	13784.40	18181.75	7925420.43	7943602.17
4	−0.05	19.20	9223.20	14899.56	5302932.13	5317831.70
5	−33.15	19.20	9223.20	16340.51	5302932.13	5319272.65
6	−36.22	2.80	9223.20	15963.83	5302932.13	5318895.96
7	−4.88	2.80	9223.20	6569.51	5302932.13	5309501.64
8	42.25	7.60	9223.20	12232.14	5302932.13	5315164.28
9	37.68	7.60	23007.60	30402.98	13228352.56	13258755.54
10	148.30	48.60	25200.00	71318.92	8800406.67	8871725.59
11	31.85	48.60	25200.00	62221.15	8800406.67	8862627.81
12	−0.15	48.60	25200.00	63522.93	8800406.67	8863929.60
13	−33.15	48.60	25200.00	68483.43	8800406.67	8868890.09
14	−33.15	48.60	7521.64	20093.31	1737509.46	1757602.77
14a	−33.15	48.60	17678.36	46352.85	7064934.47	7111287.32
15	−128.40	48.60	7521.64	31330.15	1737509.46	1768839.61
15a	−128.40	48.60	17678.36	65928.39	7064934.47	7130862.86
15b	−134.10	3.00	17678.36	63292.34	7064934.47	7128226.81
16	−160.10	48.60	7521.64	36307.10	1737509.46	1773816.56
17	−166.60	3.00	7521.64	35226.89	1737509.46	1772736.35
18	−135.10	3.00	7521.64	16675.62	1737509.46	1754185.08
19	−133.60	3.00	25200.00	81882.20	8800406.67	8882288.86
20	−40.20	3.00	25200.00	21328.14	8800406.67	8821734.81
21-NG	26.85	65.00	18849.60	51961.67	4632866.01	4684827.69
22	−0.15	65.00	18849.60	52252.78	4632866.01	4685118.80
23	−33.15	65.00	18849.60	53897.39	4632866.01	4686763.41
24	−128.40	65.00	18849.60	79044.13	4632866.01	4711910.14
25	−160.10	65.00	18849.60	91233.44	4632866.01	4724099.45
26	−166.00	1.01	18849.60	87768.62	4632866.01	4720634.63
27-LNG	−166.00	1.01	17561.45	85794.50	4446160.30	4531954.80
28	−166.00	1.01	1288.15	1300.47	187379.36	188679.83

As it was explained for drawing the diagram, total exergy destruction of the process must be calculated by varying the $\dot{E}_{D,others}$ in several stages, next a straight line can be drawn through the points. Equation of this regression line is linear type ($y = ax + b$) where the value of b is equal to the value of the endogenous part of exergy destruction in the kth component ($b = \dot{E}^{EN}_{D,k}$) [2].

Engineering method can be used to analyze any energy intensive process. But only the equipments with constant exergetic efficiency can be considered. Table 14 summarizes the advantages and disadvantages of two methods of advanced exergetic analysis.

Some additional guidelines were suggested in [25] for plotting the graph $\dot{E}_{F,tot} - \dot{E}_{L,tot} - \dot{E}_{P,tot}$ vs. $\dot{E}_{D,others}$ for correctly determining value the of $\dot{E}^{EN}_{D,k}$.

5.3. Combination of the splitting

After splitting the total exergy destruction occurring in a component into its four categories, namely endogenous, exogenous, avoidable and unavoidable parts, the task left to be done will be to evaluate how the different categories of the exergy destruction can be combined and used to provide meaningful information [25]. For obtaining applicable results, the splitting can be followed by dividing avoidable and unavoidable to endogenous and exogenous parts. Thus four different parts of irreversibility can be presented:

- Avoidable endogenous exergy destruction ($\dot{E}^{AV,EN}_{D,k}$).
- Avoidable exogenous exergy destruction ($\dot{E}^{AV,EX}_{D,k}$).
- Unavoidable endogenous exergy destruction ($\dot{E}^{UN,EN}_{D,k}$).
- Unavoidable exogenous exergy destruction ($\dot{E}^{UN,EX}_{D,k}$).

The avoidable endogenous exergy destruction $\dot{E}^{AV,EN}_{D,k}$ within component k, is calculated as below [1]:

$$\dot{E}^{UN,EN}_{D,k} = \dot{E}^{EN}_{P,k}(\dot{E}_D/\dot{E}_P)^{UN}_k \tag{8}$$

And then the avoidable exogenous exergy destruction can be calculated from Eq. (9):

$$\dot{E}^{UN,EX}_{D,k} = \dot{E}^{EN}_{D,k} - \dot{E}^{UN,EN}_{D,k} \tag{9}$$

The avoidable endogenous and the avoidable exogenous exergy destructions are then calculated by subtracting the unavoidable endogenous and unavoidable exogenous from the total endogenous and exogenous exergy destructions, respectively:

$$\dot{E}^{AV,EN}_{D,k} = \dot{E}^{EN}_{D,k} - \dot{E}^{UN,EN}_{D,k} \tag{10}$$

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

Specifications of these parts of irreversibility were presented in Table 15. In order to calculate each part of exergy destruction within all components, exergetic efficiency of the remaining components must change in order to decrease their irreversibility. Exergetic efficiency is a function of thermodynamic performance of a device. Isentropic efficiency in compressors and minimum temperature approach in heat exchangers and air coolers show this performance. For drawing the diagrams, exergy destruction in the remaining components must be reduced and effect of it on the under consideration component should be considered.

In this study isentropic efficiency of the compressors were reduced from 70% to 95% in six steps. Also in heat exchangers and air coolers minimum temperature approach were reduced during six stages.

Table 11
Thermodynamic data for MFC-Linde process material streams.

Stream no.	Temperature (°C)	Pressure (bar)	Flow (kmol/h)	Physical exergy (kW)	Chemical exergy (kW)	Total exergy (kW)
NG	13.00	60.00	25120.00	68042.09	6338117.01	6406159.10
1	35.00	33.90	18100.00	42519.89	4538001.28	4580521.17
2	35.00	27.90	25700.00	54377.07	11093539.35	11147916.43
3	35.00	16.90	34390.00	50616.31	20734535.78	20785152.08
4	3.00	60.00	25120.00	68250.59	6338117.01	6406367.61
5	3.00	33.90	18100.00	42672.32	4538001.28	4580673.60
6	3.00	27.90	25700.00	56367.27	11093539.35	11149906.63
7	8.80	16.90	34390.00	50934.41	20734535.78	20785470.19
8	8.80	16.90	20634.00	30560.65	12440721.47	12471282.11
9	8.80	16.90	13756.00	20373.77	8293814.31	8314188.08
10	−0.53	6.70	20634.00	29884.27	12440721.47	12470605.74
11	24.30	6.70	20634.00	25454.29	12440721.47	12466175.76
12	−27.00	60.00	25120.00	69886.51	6338117.01	6408003.52
13	−27.00	33.90	18100.00	43657.05	4538001.28	4581658.34
14	−27.00	27.90	25700.00	61826.19	11093539.35	11155365.54
15	−22.00	16.90	13756.00	21926.58	8293814.31	8315740.89
16	−29.58	3.00	13756.00	21357.56	8293814.31	8315171.87
17	−1.41	3.00	13756.00	10316.66	8293814.31	8304130.97
18	−85.20	60.00	25120.00	88893.67	6338117.01	6427010.68
19	−85.20	33.90	18100.00	59241.95	4538001.28	4597243.23
20	−81.50	27.90	25700.00	73524.47	11093539.35	11167063.82
21	−92.09	3.10	25700.00	71297.72	11093539.35	11164837.07
22	−31.92	3.10	25700.00	21751.88	11093539.35	11115291.23
23	−162.00	60.00	25120.00	122337.78	6338117.01	6460454.79
24	−159.00	33.90	18100.00	86156.24	4538001.28	4624157.52
25	−166.20	3.50	18100.00	84100.06	4538001.28	4622101.35
26	−87.08	3.50	18100.00	20482.36	4538001.28	4558483.64
27	35.31	6.70	13756.00	17023.00	8293814.31	8310837.31
28	28.73	6.70	34390.00	42440.87	20734535.78	20776976.64
29	75.07	16.9	34390.00	63066.99	20734535.78	20797602.77
30	62.68	15.00	25700.00	46471.14	11093539.35	11140010.49
31	35.00	15.00	25700.00	45572.28	11093539.35	11139111.64
32	76.94	27.9	25700.00	56295.50	11093539.35	11149834.86
33	57.72	25.00	18100.00	39381.52	4538001.28	4577382.81
34	35.00	25.00	18100.00	39061.28	4538001.28	4577062.56
35	63.03	33.90	18100.00	42973.13	4538001.28	4580974.42
36	−164.30	1.01	25120.00	118381.24	6338117.01	6456498.25
37	−164.30	1.01	922.48	921.33	155782.61	156703.94
LNG	−164.30	1.01	24197.52	117054.56	6182739.76	6299794.32

Table 12
Definitions for exergetic efficiency of process components.

Components exergy destruction	Exergy efficiency
Compressor $I = Ex_i - Ex_o = \sum(\dot{m} \cdot e)_i + W - \sum(\dot{m} \cdot e)_o$ [31]	$\varepsilon = \frac{\sum(\dot{m} \cdot e)_i - \sum(\dot{m} \cdot e)_o}{W}$ [31]
Air cooler $I = Ex_i - Ex_o = \sum(\dot{m} \cdot e)_i + e_{ai} + W - \sum(\dot{m} \cdot e)_o - e_{ao}$	$\varepsilon = \frac{\sum(\dot{m} \cdot e)_o + e_{ao}}{\sum(\dot{m} \cdot e)_i + W}$
Heat exchanger $I = Ex_i - Ex_o = \sum(\dot{m} \cdot e)_i - \sum(\dot{m} \cdot e)_o$ [31]	$\varepsilon = 1 - \left[\left\{\frac{\sum_1^n(\dot{m} \cdot \Delta e)}{\sum_1^n(\dot{m} \cdot \Delta h)}\right\}_h - \left\{\frac{\sum_1^m(\dot{m} \cdot \Delta e)}{\sum_1^m(\dot{m} \cdot \Delta h)}\right\}_c\right]$ [37]
Pump $I = Ex_i - Ex_o = \sum(\dot{m} \cdot e)_i + W - \sum(\dot{m} \cdot e)_o$ [31]	$\varepsilon = \frac{\sum(\dot{m} \cdot e)_i - \sum(\dot{m} \cdot e)_o}{W}$ [31]
Expansion valve $I = Ex_i - Ex_o = \sum(\dot{m} \cdot e)_i - \sum(\dot{m} \cdot e)_o$ [31]	$\varepsilon = \frac{e_o^{\Delta T} - e_i^{\Delta T}}{e_i^{\Delta P} - e_o^{\Delta P}}$ [31]
Separator/mixer $I = Ex_i - Ex_o = \sum(\dot{m} \cdot e)_i - \sum(\dot{m} \cdot e)_o$ [31]	$\varepsilon = \frac{\sum(\dot{m} \cdot e)_o}{\sum(\dot{m} \cdot e)_i}$ [31]
Cycle/process *Summation of irreversibility of all devices* [31]	$\varepsilon = 1 - \frac{Total\ irreversibility\ of\ cycle}{Total\ consumed\ power\ in\ cycle}$ [38]

6. Results and discussion

6.1. Conventional exergy analysis

Results of exergy analysis of five conventional LNG processes were presented in Table 16. As can be seen for SMR-Linde, compressor C-1 has the maximum value of exergy destruction (13676.34 kW) and after that precooling stage heat exchangers (E-1 and E-2) and compressor C-2/1 lose a lot of work. Exergy efficiency of expansion valves is less than the others but their irreversibilities are low. This shows that performance of the devices must be considered in terms of both lost work and exergy efficiency simultaneously.

Table 13
Assumptions made for unavoidable conditions.

Component	Unavoidable conditions
Compressor	Isentropic efficiency = 90%
Multi stream heat exchanger	Minimum temperature approach = 0.5 °C
Air cooler	Minimum temperature approach = 5 °C

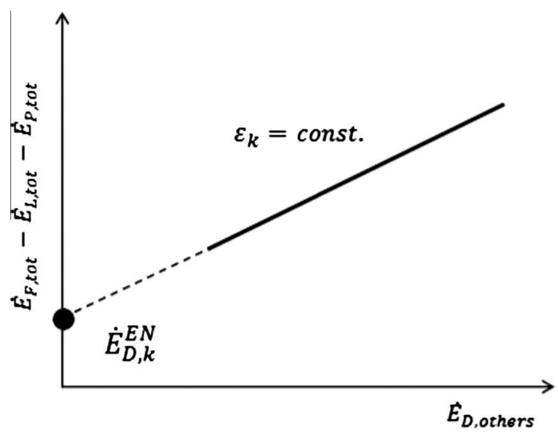

Fig. 11. Illustration of engineering method $\dot{E}^{EN}_{D,k}$.

The results for SMR-APCI are shown that maximum value of irreversibility is related to the heat exchanger E-2 which the liquefaction and subcooling the natural gas occurs in it and its efficiency is 91.02%. The least value of efficiency belongs to valve V-2 which 6438.07 kW of exergy is destroyed. Exergetic efficiency of the process was 45.09% that is higher than the SMR-Linde (40.2%). The C3MR process analysis results show irreversibility of compressor C-2 is more than other components while its efficiency is 77.27%.

Expansion valve V-1 destroys almost 3000 kW of exergy whereas its efficiency is very low. The important point is performance of heat exchangers which is related to their thermal design. Exergetic efficiency of the propane cycle, mixed refrigerant cycle and the process were gained 47.5%, 52.75% and 50.98% respectively. Also results of DMR and MFC analysis were presented in Table 16.

Table 16
Results of the conventional exergetic efficiency of processes.

Components, *k*		Exergy destruction (kW)	Exergetic efficiency (%)
SMR Linde			
C-1	Compressor	13676.44	79.63
C-2/1	Compressor	12173.45	79.77
C-2/2	Compressor	6050.30	78.52
AC-2	Air cooler	6571.72	95.26
E-1	Heat exchanger	12291.91	88.32
E-2	Heat exchanger	12811.30	91.28
E-4	Heat exchanger	4271.57	91.62
SMR APCI			
C-1	Compressor	10423.75	79.43
C-2	Compressor	9194.03	78.19
C-3	Compressor	7887.98	79.20
E-1	Heat exchanger	2562.93	98.66
E-2	Heat exchanger	14311.54	91.02
C3MR			
C-1/3	Compressor	6066.40	77.60
C-2	Compressor	9840.40	77.27
C-3/1	Compressor	4499.20	78.94
C-3/2	Compressor	2950.29	78.22
E-2A	Heat exchanger	5518.60	95.98
DMR			
C-1	Compressor	11293.57	81.57
C-3	Compressor	3850.74	79.02
AC-1	Air cooler	5538.17	92.25
E-3	Heat exchanger	4594.94	91.97
MFC			
C-1/1	Compressor	2170.60	75.55
C-1/2	Compressor	5692.45	78.37
C-2/1	Compressor	7305.66	77.19
C-2/2	Compressor	2937.88	78.49
C-3/1	Compressor	5832.40	76.42
AC-1	Air cooler	7077.60	88.87
E-2	Heat exchanger	3255.50	97.25
E-3	Heat exchanger	3259.30	94.74

In DMR process, compressor C-1 has high irreversibility and efficiency of valve V-1 is also less than the other devices. Exergetic efficiency of the first and second mixed refrigerant cycles and whole process are 50.39%, 46.68% and 48.78%, respectively. In MFC process, compressor C-2/1 and air cooler AC-1 have high amount of lost work and exergetic efficiency of expansion valves E-1 and E-2 are less than the others despite of low exergy

Table 14
Advantages and disadvantages of two methods [25].

Advantages	Disadvantages
Thermodynamic method	
This method can be applied to all thermal systems	The application to power plant systems has not as yet been demonstrated In addition, this method requires the ideal operation of a component to be defined. The ideal operation of some components can only be approximately determined
Engineering method	
An accurate procedure which can be applied to both simple and complex thermal systems	Unable to determine the endogenous exergy destruction for dissipative devices such as throttle valves. A long and perhaps time consuming procedure

Table 15
Specifications of each part of irreversibility [25].

Endogenous	Exogenous
Avoidable	
Can be reduced through an improvement of the efficiency of the *k*th component	Can be reduced by a structural optimization of the overall system or by improving the efficiency of the remaining components
Unavoidable	
Cannot be reduced because of technical and process limitations for the *k*th component	Cannot be reduced because of technical and or process limitations in other components of the overall system for the given structure

destruction. Efficiency for three cycles was calculated 45.7%, 62.5% and 42.86%, respectively and for whole process is 51.82%.

6.2. Advanced exergy analysis

Table 17 shows results of the advanced exergetic analysis of the processes, separately. The results were obtained by drawing diagrams of $\dot{E}_{D,tot}$ vs. $\dot{E}_{D,others}$. Diagrams of SMR-Linde were presented in Fig. 12. These diagrams show that a linear relation exists between $\dot{E}_{D,tot}$ and $\dot{E}_{D,others}$ as it's been proven in [25] mathematically. The linear dependence makes the value of intercept of lines equal to endogenous exergy destruction approximately. As can be seen in the figures, amount of the effectiveness of irreversibilities produced within other components on the under considering component can be realized by slope of the straight line of $\dot{E}_{D,tot}$ and $\dot{E}_{D,others}$ diagram. The greater slope means the higher effectiveness. Also it should be noted that in advanced exergetic analysis, the important point is that how much of exergy destruction has been produced within the components and how much of it (endogenous or exogenous) is avoidable. In this research the components with high inefficiency according to [25] were considered.

Table 17 shows results of the advanced exergy analysis of SMR-Linde process. Also Fig. 13 presents different parts of components irreversibility separately. As can be seen most of the exergy destructions in components except air cooler AC-2 are endogenous. High levels of endogenous exergy destruction show that component interactions do not contribute to the thermodynamic inefficiencies significantly. Exogenous exergy destruction produced by multi stream heat exchanger E-2 is more than the other exchangers and in the case of E-4 all irreversibilities is endogenous. With improved process design procedures portion of the exogenous exergy destruction can be changed significantly. This condition usually occurs within some devices of the process which operating condition of their inlet streams do not change with decreasing the exergy destructions in other components. Compressor C-2/2 produces high amount of exogenous irreversibility. Endogenous inefficiencies in air cooler AC-2 is more than exogenous one, because irreversibilities of compressors C-1 and C-2/1 and air cooler AC-1

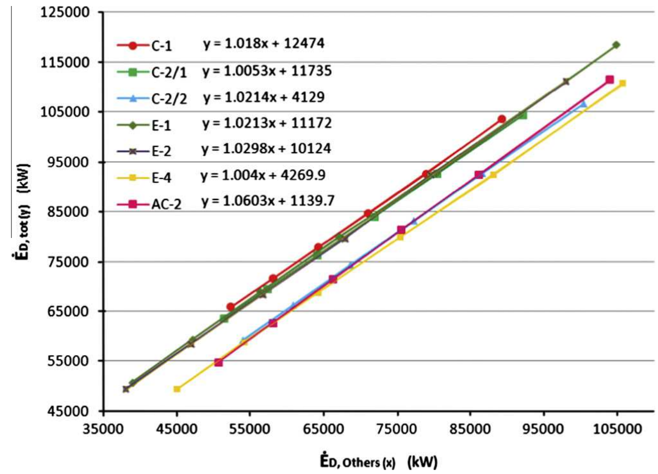

Fig. 12. Diagram of $\dot{E}_{D,tot}$ vs. $\dot{E}_{D,others}$ for SMR-Linde process components.

Table 17
Results of the advanced exergetic analysis of processes.

Component, *k*	Exergy destruction categories (kW)							
	$\dot{E}^{EN}_{D,k}$	$\dot{E}^{EX}_{D,k}$	$\dot{E}^{UN}_{D,k}$	$\dot{E}^{AV}_{D,k}$	$\dot{E}^{AV,EN}_{D,k}$	$\dot{E}^{AV,EX}_{D,k}$	$\dot{E}^{UN,EN}_{D,k}$	$\dot{E}^{UN,EX}_{D,k}$
SMR Linde								
C-1	12474.00	1202.44	4811.05	8865.39	8254.60	610.79	4219.40	591.65
C-2/1	11735.00	438.45	4277.38	7896.07	7751.60	144.47	3983.40	293.98
C-2/2	4129.00	1921.30	2090.47	3959.83	2680.50	1279.33	1448.50	641.97
AC-2	1139.70	5432.02	3539.64	3032.08	377.00	2655.08	762.70	2776.94
E-1	11172.00	1119.91	7316.31	4975.60	4349.30	626.30	6822.70	493.61
E-2	10124.00	2687.30	9777.48	3033.82	2228.90	804.92	7895.10	1882.38
E-4	4271.57	0.00	3273.01	998.56	998.56	0.00	3273.01	0.00
SMR APCI								
C-1	6986.60	3437.15	3706.47	6717.28	4561.40	2155.88	2425.20	1281.27
C-2	9056.80	137.23	3174.98	6019.05	6015.60	3.45	3041.20	133.78
C-3	6641.60	1246.38	2742.52	5145.46	4402.50	742.96	2239.10	503.42
E-1	2562.93	0.00	2144.03	418.90	418.90	0.00	2144.03	0.00
E-2	8425.50	5886.04	13311.81	999.73	840.20	159.53	7585.30	5726.51
C3MR								
C-1/3	4540.20	1526.20	2086.44	3979.96	2995.88	984.08	1544.32	542.12
C-2	9504.10	336.30	3425.18	6415.22	6105.69	309.53	3398.41	26.77
C-3/1	4337.10	162.10	1567.02	2932.18	2849.60	82.58	1487.50	79.52
C-3/2	2730.50	219.79	1017.27	1933.02	1795.38	137.64	935.12	82.15
E-2A	3961.20	1557.40	5420.51	98.09	35.06	63.03	3926.14	1494.37
DMR								
C-1	10039.00	1254.57	4099.24	7194.33	6548.14	646.19	3490.86	608.38
C-3	3674.10	176.64	1338.82	2511.92	2494.54	17.38	1179.56	159.26
AC-1	1433.90	4104.27	4684.57	853.60	252.00	601.60	1181.90	3502.67
E-3	3443.20	1151.74	4504.71	90.23	85.72	4.51	3357.48	1147.23
MFC								
C-1/1	2090.00	80.60	733.72	1436.88	1394.80	42.08	695.20	38.52
C-1/2	5460.70	231.75	1967.89	3724.56	3649.49	75.07	1811.21	156.68
C-2/1	7269.40	36.26	2533.72	4771.94	4747.90	24.04	2521.50	12.22
C-2/2	2857.00	80.88	1016.52	1921.36	1854.70	66.66	1002.30	14.22
C-3/1	5789.10	43.30	2035.52	3796.88	3773.67	23.21	2015.43	20.09
AC-1	5264.40	1813.20	2404.15	4673.45	3467.56	1205.89	1796.84	607.31
E-2	3202.70	52.80	2615.40	640.10	606.39	33.71	2596.31	19.09
E-3	2535.30	724.00	2975.66	283.64	255.67	27.97	2279.63	696.03

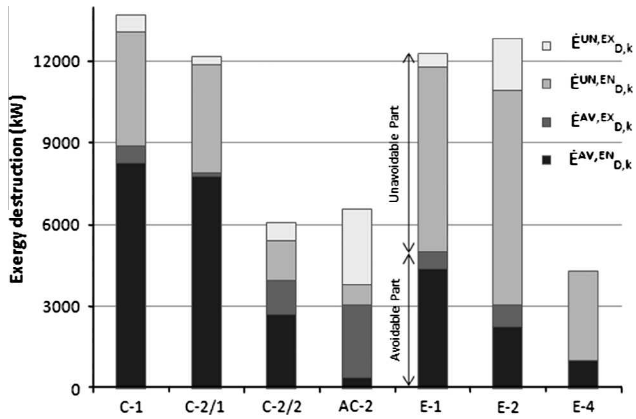

Fig. 13. Splitting of component exergy destruction to endogenous/exogenous and avoidable/unavoidable parts: SMR-Linde.

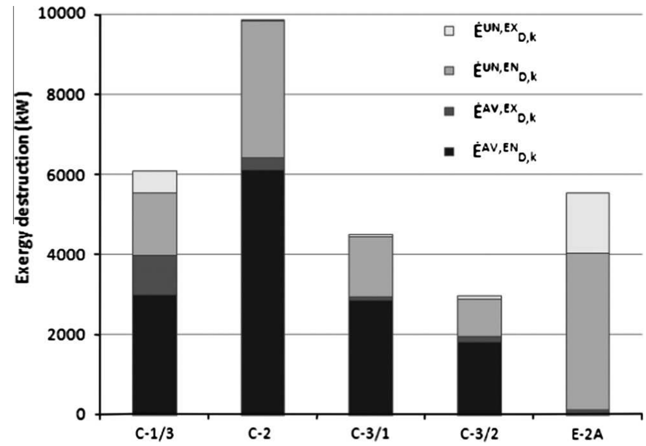

Fig. 15. Splitting of component exergy destruction to endogenous/exogenous and avoidable/unavoidable parts: C3MR-Linde.

are induced to it. In Table 17 it is clear that most of the inefficiencies produced by compressors are avoidable and thermodynamic efficiency of the process can be enhanced by improving performance of these components. But in the case of heat exchangers and air cooler most of the exergy destructions are unavoidable.

Results of advanced exergetic analysis of SMR-APCI process were provided in Table 17 and Fig. 14. In this process also, most of the exergy destructions are endogenous, and inefficiencies in compressor C-2 and heat exchangers E-1 are approximately endogenous. In heat exchanger E-2 about 41.12% of exergy destruction is exogenous and according to the process configuration this amount of irreversibility can be induced from heat exchanger E-1. About 65% of exergy destructions within compressors are avoidable that shows potential of the process efficiency for improving. Total irreversibility of compressor C-2 is endogenous because it is located after mixer MIX-1.

Table 17 and Fig. 15 show results of the advanced exergetic analysis of C3MR-Linde process. As can be seen exergy destructions produced by compressors C-2, C-3/1 and C-3/2 are endogenous. While 25.16% irreversibility of C-3/1 is exogenous and it can be induced from compressor C-2 and air cooler AC-1. For heat exchanger E2-A which has a great heat duty, exogenous inefficiency is about 28.22% of total exergy destruction but approximately all of it is unavoidable. Most of the exergy destructions within compressors are avoidable.

Results of the advanced exergetic analysis which was carried out on the DMR-APCI process were presented in Table 17 and Fig. 16. As can be seen, portion of endogenous exergy destruction in compressors and heat exchangers is high, but in air cooler AC-1 there is high amount of exogenous inefficiency which can be induced from compressor C-2. All irreversibility produced within heat exchanger is unavoidable; however in compressors about 65% of exergy destructions are avoidable.

Table 17 and Fig. 17 show results of the advanced exergetic analysis of MFC-Linde process. Exergy destructions of compressors C-1/1, C-2/1, C-2/2 and C-3/1 and heat exchanger E-2 are endogenous and were produced through performance of the components. There are exogenous exergy destructions for compressor C-1/2, air cooler AC-1 and heat exchanger E-3 which were induced from the other components. But as this figure show most of the exergy destructions produced within the components are avoidable and by using the efficient devices, efficiency of the process can be improved significantly. Irreversibilities in heat exchangers E-2 and E-3 are more unavoidable.

Comparing between results of analyses carried out on the plants show that the exogenous exergy destruction within air coolers is approximately more than other components. One reason for this case is position of the compressors that locate before them.

Mechanism of inefficiency induction from remaining components to under consideration component changes the pressure and temperature of the component outlet stream. Here, temperature of the outlet stream from a compressor with high irreversibility

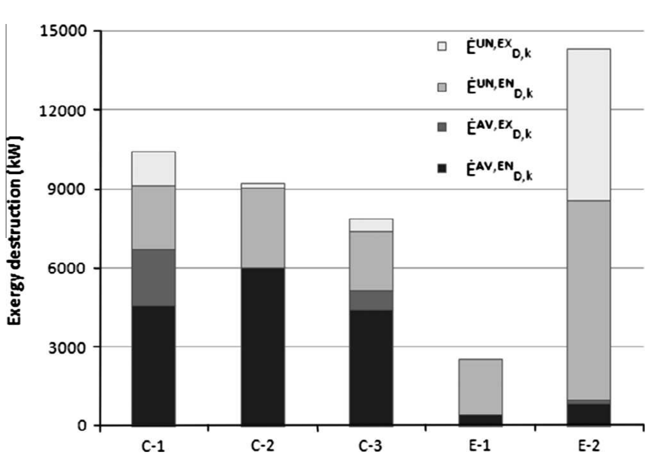

Fig. 14. Splitting of component exergy destruction to endogenous/exogenous and avoidable/unavoidable parts: SMR-APCI.

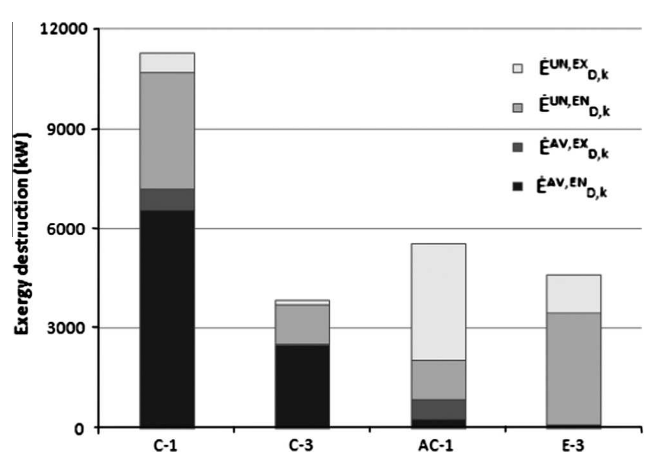

Fig. 16. Splitting of component exergy destruction to endogenous/exogenous and avoidable/unavoidable parts: DMR-APCI.

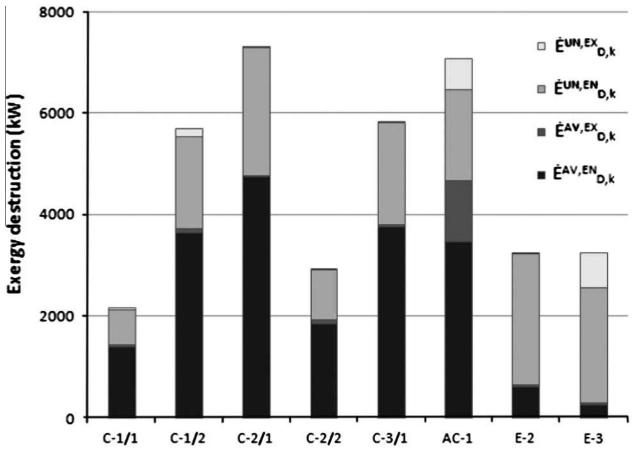

Fig. 17. Splitting of component exergy destruction to endogenous/exogenous and avoidable/unavoidable parts: MFC-Linde.

increases and this can increase the irreversibility of the next devices like an air cooler.

Table 18 shows percent of avoidable exergy destruction per total exergy destruction of each process. As can be seen in Linde processes (C3MR and MFC) percentage of avoidable inefficiency is high and this point indicates that these processes have more potential to improve in energy consumption. One reason for this is number of the equipment were used in the Linde processes.

As discussed, after detecting a component with high irreversibility next step will be decreasing its malfunction. Table 15 explains general strategies in order to face with each part of exergy destruction. Avoidable exergy destruction shows potential of the process for improving so an engineer or a designer must focus on this part of irreversibility. In the case of avoidable endogenous part, some ways such as replacing the components with efficient devices or optimizing their performance or designing new components can be used. For changing the avoidable exogenous part, efficiency of the remaining components should be improved or designing and configuration of the process and connections between them should be optimized. Some of the components with high avoidable exergy destruction and suggested strategies for reducing their irreversibility were provided in Table 19.

Note that exergy destruction in most of the components is endogenous, so a strategy can be used for improving their efficiency. For air coolers strategies B and C should be used because of their exogenous inefficiency. In the case of some components with low exogenous exergy destruction, it's important to use strategy B without C because replacing one or several components or improving their efficiencies is more economical than performing structural optimization on the whole process.

Table 18
Percent of avoidable exergy destruction per total exergy destruction.

Process	Total avoidable exergy destruction (kW)	Total exergy destruction (kW)	Percent
SMR-Linde	32761.35	67846.69	48.29
SMR-APCI	19300.42	44380.23	43.49
C3MR	15358.47	28874.89	53.19
DMR	10650.08	25277.42	42.13
MFC	21248.81	37531.39	56.62

7. Conclusions

In this paper, five conventional mixed refrigerant liquefaction processes were considered in order to analyze through conventional and advanced exergy analysis. Four parts of irreversibility (avoidable/unavoidable) and (endogenous/exogenous) were calculated for the components with high inefficiencies. Results of the exergy analysis showed that exergy destruction within compressors and multi stream heat exchangers were higher than the other components. Results of the advanced exergetic analysis also showed that most of the irreversibilities within the components

Table 19
Strategies for reducing avoidable exergy destruction.

Process	Component, *k*	Exergy destruction categories (kW)				The part should be focused	Possible strategies to reduce exergy destruction		
		$\dot{E}_{D,k}$	$\dot{E}^{AV}_{D,k}$	$\dot{E}^{AV,EN}_{D,k}$	$\dot{E}^{AV,EX}_{D,k}$		Strategy A[a]	Strategy B[b]	Strategy C[c]
Compressor									
SMR-Linde	C-1	13676.44	8865.39	8254.60	610.79	EN.	•		
	C-2/1	12173.45	7896.07	7751.60	144.47	EN.	•		
SMR-APCI	C-1	10423.75	6717.28	4561.40	2155.88	EN./EX.	•	•	•
	C-2	9194.03	6019.05	6015.60	3.45	EN.	•		
	C-3	7887.98	5145.46	4402.50	742.96	EN.	•	•	
C3MR	C-1/3	6066.40	3979.96	2995.88	984.08	EN./EX.	•	•	
	C-2	9840.40	6415.22	6105.69	309.53	EN.	•		
DMR	C-1	11293.57	7194.33	6548.14	646.19	EN.	•		
MFC	C-1/2	5692.45	3724.56	3649.49	75.07	EN.	•		
	C-2/1	7305.66	4771.94	4747.90	24.04	EN.	•		
	C-3/1	5832.40	3796.88	3773.67	23.21	EN.	•		
Air cooler									
SMR-Linde	AC-2	6571.72	3032.08	377.00	2655.08	EX.		•	•
DMR	AC-1	5538.17	853.60	252.00	601.60	EN./EX.	•	•	•
MFC	AC-1	7077.60	4673.45	3467.56	1205.89	EN./EX.	•	•	•
Heat exchanger									
SMR-Linde	E-1	12291.91	4975.60	4349.30	626.30	EN.	•	•	
	E-2	12811.30	3033.82	2228.90	804.92	EN./EX.	•	•	•
	E-4	4271.57	998.56	998.56	0.00	EN.	•		
SMR-APCI	E-2	14311.54	999.73	840.20	159.53	EN.	•	•	
MFC	E-2	3255.50	640.10	606.39	33.71	EN.	•		

[a] Strategy A: Improving the efficiency of the *k*th component or replacing the component with efficient devices.
[b] Strategy B: Improving the efficiency of the remaining components.
[c] Strategy C: Structural optimization of the overall system.

were endogenous and avoidable inefficiencies of compressors were higher than the other parts despite of the heat exchangers. The following lines are important results obtained through applying advanced exergetic analysis on the liquefaction processes:

- Amount of the effectiveness of irreversibilities were produced within others components on the under considering component can be realized by slope of the straight line of $\dot{E}_{D,tot}$ and $\dot{E}_{D,others}$ diagram. The greater slope means the higher effectiveness. For example in the DMR-APCI process, exogenous exergy destruction of AC-1 air cooler is more than compressor C-3, as the slope of the air cooler line is greater than the compressor.
- Mechanism of inefficiency induction from remaining components to under consideration component changes the pressure and temperature of the component outlet stream. For example temperature of the outlet stream from a compressor with high irreversibility increases and this can increase the irreversibility of the next devices like an air cooler. Thus, improvement in energy efficiency of a component in a process can decreases the exergy destruction in it and also in the other components which have interactions with.
- Process design in some processes makes value of the exogenous exergy destruction within components very low. For example in SMR-APCI process, irreversibility of the heat exchangers is totally endogenous and does not relate to remaining components.

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