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ORIGINAL RESEARCH PAPER

Advanced exergy and exergoeconomic analysis of the integrated structure of simultaneous production of NGL recovery and liquefaction

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ABSTRACT: Advanced exergoeconomic analysis is applied on process configurations for co-production of LNG and NGL. This analysis provides information on the origin of the irreversibility as well as the irreversibility value of the process. The exergy destruction, exergy destruction cost, and also investment cost, are divided into two available/unavailable and endogenous/exogenous parts. The results of advanced exergy analysis show that in C1MR2, AC20, AC1, AC4, AC5 equipment, a large part of the irreversibility is due to the exogenous exergy destruction, and in other equipment, it is due to the endogenous exergy destruction. Except for the MSHX1 heat exchanger, the available exergy destruction equipment is more than the unavailable one, which indicates that by improving the efficiency of these equipment, a decrease in losses is possible in the system. In advanced exergoeconomic analysis, it is also shown that the priority should be to improve system performance on MSHX1, CMR1 and C1MR3, because in comparison with other equipment, it has the highest cost of endogenous available exergy destruction.

KEYWORDS*: advanced exergy analysis, advanced exergoeconomic analysis, Integration, LNG, NGL*

INTRODUCTION

After gas sweetening and dehumidification, the natural and dried gas should have the technical transmission characteristic to be located in the pipeline transmission cycle and injection into global network, so that along the transmission path, the single gas phase (gas phase) should be preserved to avoid the liquefaction problems of hydrocarbon compounds, and as a result, two-phase flow in the pipeline. The pipeline gas transmission is always associated with pressure drop and temperature drop. This phenomenon can provide a suitable condition for isolation of heavy hydrocarbons from gas flow [1]. The hydrocarbons heavier than methane, whether in terms of thermal value or in conversion processes are considered beneficial compounds, and in addition to domestic consumption, they can be considered as export items. The productive NGL is also a feed of downstream units such as olefin or aromatic units, and with its processing and separation, a considerable added value can be obtained. From the downstream products obtained from NGL, the ethane, LPG and pyrolysis gasoline can be mentioned. This product is one of the most important feeds for petrochemical units such as aromatic and olefin units. Thus, the isolation of heavier compounds is essential, which can also produce useful products [1]. Hence, in this research, these two units are designed simultaneously. The simultaneous design of the units and integration of processes reduces the number of required equipment and energy consumption. Vatani et al., developed an integrated structure of the simultaneous production of NGL, natural gas liquefaction, natural gas production with domestic and industrial consumption based on the C3MR refrigeration cycle, with specific power consumption of 0.414 kWh/kgLNG and ethane recovery of 93%. Using the HYSYS software connection method in Matlab programming and optimization environment of the genetic algorithm, they optimized the specific energy consumption as a target function, this structure can be used for large LNG units in natural gas refineries [2]. Mehpooya et al. developed three new integrated structures for simultaneous production of NGL and natural gas liquefaction based on C3MR, DMR and MFC refrigeration cycle, respectively, with total cycle exergy efficiency of 55%, 56% and 59%, with specific power consumption of 0.391, 0.375, and 0.364 kWh/kgLNG, and focused on exergoeconomic analysis of the given integrated systems in 2016 [3]. Mohd Shariq Khan et al. (2014) developed a new optimization algorithm for the integrated refrigeration cycle for the simultaneous production of NGL and LNG [4]. The Linde Company provided three integrated industrial systems for the simultaneous production of NGL and LNG with LNG production of 200 tons per day [5]. Hosanna Uwitonze et al. (2016) presented three mixed refrigerant dual refrigeration cycle structures in the ultra-cold natural gas integrated processes (NGL, LNG). For sensitivity analysis of integrated structures, the effect of methane composition

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Nomenclature

C	Cost per exergy unit ($/J)
$\dot{C}$	Exergy cost rate ($/hr)
$\dot{E}$	Total exergy rate (kW)
$\dot{Z}_K$	Capital investment cost rate ($/hr)
	Superscripts
AV	Avoidable
EN	Endogenous
EX	Exogenous
UN	Unavoidable
CH	Chemical
	Subscripts
D	Destruction
i	Substance i, inlet
k	kth component
L	Loss
O	Outlet
tot	Total
	Greek Symbols
Δ	Gradient
	Abbreviations
AC	Air cooler
C	Compressor
C3MR	Propane precooling
D	Flash drum
DMR	Dual mixed refrigerant
HX	Heat exchanger
hr	Hour
LNG	Liquefied natural gas
MR	Mixed refrigerant
MFC	Mixed fluid cascade
NG	Natural gas
NGL	Natural gas liquids
T	Tower
V	Expansion valve
T	Temperature (°C)

changes and intake feed mass flow on the specific power consumption was investigated [6]. Ghorbani et al., developed an integrated structure for the removal of nitrogen from natural gas and simultaneous production of LNG and NGL. For supply of developed structure cooling, a MFC refrigeration cycle has been used, the exergy efficiency and specific power consumption of integratedstructure are 62.82%, 0.32 kWh/kg LNG, respectively [7].

The main aim of this research is to develop a processing integrated structure of NGL recovery and liquefaction, where the advanced exergy and exergoeconomic analysis has been used for feasibility of the developed structure.

PROCESS DESCRIPTION

In this research, the integrated structures in Hysys software were developed, and by connecting this software to Matlab programming software, the simulation is completed. Peng–Robinson equation of state (PR) is used for primary simulation, because this equation of state has excellent accuracy in a wide range of temperature and pressure conditions in predicting the properties of light hydrocarbons (which are used in LNG production processes). There are numerous scientific articles that use Peng–Robinson equation of state to design the processing integrated structures. In these articles, C1 to C5 hydrocarbons and nitrogen were used as a refrigerant for cooling supply of the processing structures [8].

One of the solutions proposed for maximum recovery of ethane from natural gas flow is to provide the required backflow with minimum temperature. In this structure, the gas subcooled process method presented in the reference [1] is used to reach the maximum ethane recovery with minimum costs. The information of the structure simulation of LNG/ NGL recovery are presented in the reference[1]. The diagram of the developed process flow is presented in Figure1.

The natural gas enters the HX1 heat exchanger, and temperatures is reduced up to -42 °C. Flow 1 enters D1 after leaving the heat exchanger, and separation of a part of heavy hydrocarbons is done on this equipment. Flow 4, which is part of the productive liquid D1, enters de-ethanizer tower after passing through the expansion valve V1. Flow 2, which is part of the productive gas of D1, enters the EX1 expander and its pressure is increased by 25. Flow 8, which is an expandable output enters the de-ethanizer tower at the temperature of -80ºC. The temperature of flows 3 and 6 is reduced by passing through the HX2 heat exchanger to an approximate value of 75°C, and, enters the de-ethanizer tower by passing through expansion valves V2 and V3, respectively. The de-ethanizer tower contains 30 trays and operated at pressure of 24. The tower bottom output is NGL of process production. In this tower, the hydrocarbons heavier than methane are recovered more than 90%, and residual gas (natural gas) is exhausted from top of tower at temperature of 90°C and pressure of 23 bar.

The natural gas flow is divided into G1 and G2. The C7 compressor output flow enters the HX3 heat exchanger and the temperature is decreased up to -105°C. Flow G13 enters HX4 heat exchanger after passing through expansion valve V12. The temperature of flows G11 and G16 is reduced to a value of -153°C by passing through the HX4 heat exchanger. The sum of output liquid flows from the D5 and D6 is the productive LNG process, also, the sum of output gas flows from D5 and D6 makes up the flow G21p, which reaches to the pipeline conditions after returning to the process. The propane pre-cold refrigeration cycle flow is shown with green lines. C1MR1, C2MR2 and C3MR3 are propane refrigeration cycle compressors, and propane is removed from dense sector at a temperature of -38°C and a pressure of 22 bar.

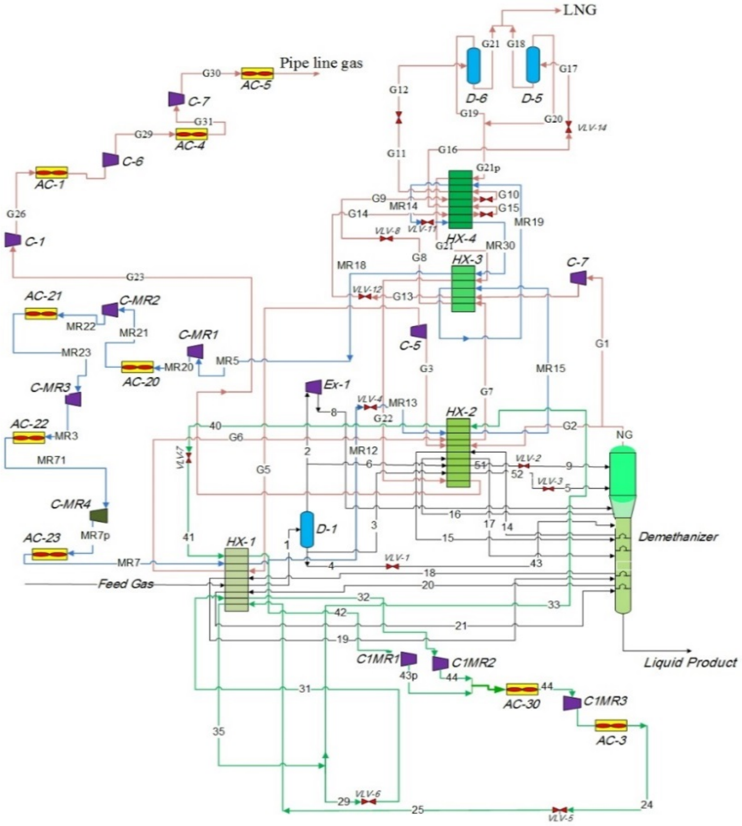

Fig. 1. Diagram of process flow of the developed simultaneous production [1]

Table 1
Development methodology of integrated structure of the simultaneous production.

Type of process	LNG/NGL
Integration methodology	Diagram of Exergy Composite Curve (Thermal and power integration)
Refrigeration cycle	C3MR
Simulation tool	Simulation software - Aspen – Hysys
Thermodynamic equations	Prediction of the thermodynamic properties of multi-component refrigerants and phase equilibrium calculations using Hysys simulation software (Peng–Rabinson equation of state is used to calculate the vapor phase equilibrium and liquid of multi-component refrigerant and prediction of enthalpy and entropy).
Feasibility	The main aim of this research 1.Advanced exergy analysis 2.Economic analysis in advanced exergoeconomic method

Advanced exergy analysis

In the exergy analysis, although the irreversibility of the devices can be determined, but these irreversibility cannot be divided because of their origin. The advanced exergy analysis is carried out based on the results of exergy analysis, in this analysis; the irreversibility of equipment is divided into two viewpoints: one of them is from viewpoint of origin of the irreversibility, and the other one is from viewpoint of overcoming irreversibility.

From the first viewpoint, the irreversibility of each device is divided into two categories of endogenous irreversibility and exogenous irreversibility. The exogenous irreversibility is a part of the irreversibility, which is the induction effect of irreversibility in other devices. Therefore, in this viewpoint, the exergy destruction of k component can be seen as follows:

$$\dot{E}_{D,k} = \dot{E}^{EN}_{D,k} + \dot{E}^{EX}_{D,k} \qquad (1)$$

There are two methods to calculate the endogenous exergy destruction.

The thermodynamic and engineering methods, and in this paper, the engineering method is used. Hence, for each process component, the total exergy destruction diagram should be depicted based on deductive exergy destruction of equipment based on the following equations as shown in Figure 2.

$$\dot{E}_{D,tot} = \dot{E}_{F,tot} - \dot{E}_{P,tot} \tag{2}$$

$$\dot{E}_{D,tot} = \sum_{k} \dot{E}_{D,k} = \dot{E}_{D,k} + \dot{E}_{D,others} \tag{3}$$

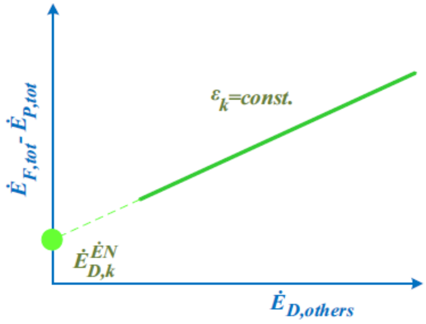

Fig. 2. Schematic of the engineering method to calculate the endogenous exergy destruction.

The intersection of this diagram with the vertical axis shows the endogenous exergy destruction of k component. The exergy efficiency of k component must be constant while drawing this diagram.

By calculating endogenous exergy destruction and the following equation, the exogenous exergy destruction can be obtained.

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

From the viewpoint of overcoming irreversibility, the irreversibility of each device is divided into two parts of the avoidable irreversibility and unavoidable irreversibility. The unavoidable irreversibility ($\dot{E}^{UN}_{D,k}$) is part of the irreversibility that cannot be overcome. The overcoming or not-overcoming criteria of irreversibility is technical and economic constraints in the design, construction or selection of devices. From this viewpoint, the exergy destruction can be written as follows:

$$\dot{E}_{D,k} = \dot{E}^{UN}_{D,k} + \dot{E}^{AV}_{D,k} \tag{5}$$

In this paper, the assumptions for unavoidable irreversibility are considered as shown in Table 2.

Table 2

Assumptions for advanced exergoeconomic analysis.

Equipment	Operational conditions
Compressor	90 %
Multi-stream Heat Exchanger	$\Delta T_{\min} = 0.5$ ºC
Air cooler	$\Delta T_{\min} = 5$ ºC

The unavoidable and avoidable exergy destruction can be calculated from the following equations:

$$\dot{E}^{UN}_{D,k} = \dot{E}_{P,k} \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{UN} \tag{6}$$

$$\dot{E}^{AV}_{D,k} = \dot{E}_{D,k} - \dot{E}^{UN}_{D,k} \tag{7}$$

In the following, for better understanding of the role of each component in the process, these irreversibilities can be combined.

As a result, four categories of endogenous unavoidable irreversibility, exogenous unavoidable irreversibility, endogenous avoidable irreversibility, exogenous avoidable irreversibility are obtained.

Endogenous and exogenous unavoidable irreversibility is defined as follows:

$$\dot{E}^{UN,EN}_{D,k} = \dot{E}^{EN}_{P,k} \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{UN} \tag{8}$$

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

Therefore, the endogenous and exogenous avoidable irreversibility is also obtained from the following equations:

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

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

Exergoeconomic analysis

Exergoeconomic analysis is a combination of exergy analysis and economic analysis.

The purpose of this analysis is to obtain the exergy cost of each flow. First, the exergy of each of the process flows must be determined. Then, the cost of capital for each equipment should be calculated, and then, the equilibrium equation for each component should be written. In general, this equation is as follows:

$$c_{F,k}\dot{E}_{F,k} + \dot{Z} = c_{P,k}\dot{E}_{P,k} \tag{12}$$

For components with more than one output flow, the auxiliary equations are required. Therefore, by writing the above equations for all process components as well as auxiliary equations, a linear equation system is obtained, including unknowns of exergy unit cost of each flow. By solving this system, in addition to these unknowns, the exergy cost of each flow should be calculated by the following equation.

$$\dot{C} = c\dot{E} \tag{13}$$

The exergy destruction cost can also be calculated from the following equation.

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \tag{14}$$

Advanced exergoeconomic analysis

Similar to the advanced exergy analysis, the exergy destruction cost and investing cost of each component is divided in two categories of endogenous/exogenous and avoidable/unavoidable in the advanced exergoeconomic analysis. Through the following equations, the endogenous, exogenous, avoidable, and unavoidable exergy destruction cost value can be obtained.

The combination of endogenous/exogenous with avoidable/unavoidable exergy destruction leads to the following equations.

The endogenous/exogenous and avoidable/unavoidable investment cost for each component is calculated from the following equations:

Once again, similar to the previous section, the following equations are obtained by combining the irreversibility.

RESULTS AND DISCUSSION

In Figure 3, for different process equipment, the total exergy destruction diagram is plotted based on deductive exergy destruction of desired equipment. As can be seen, there is a linear relationship between these two parameters. The width of the origin of this diagram for each component indicates the endogenous loss exergy of that equipment. The MSHX1 exchanger with 5900.9 kW, the compressors CMR1 with 3863.7 kW, C1MR3 with 3863.7 kW, and C1MR3 with 3099.3 kW, have the highest endogenous exergy destruction. The aircrafts AC1 with 32.013 kW, AC4 with 69.929 kW, and AC5 with 94.111 kW have also the lowest endogenous exergy destruction.

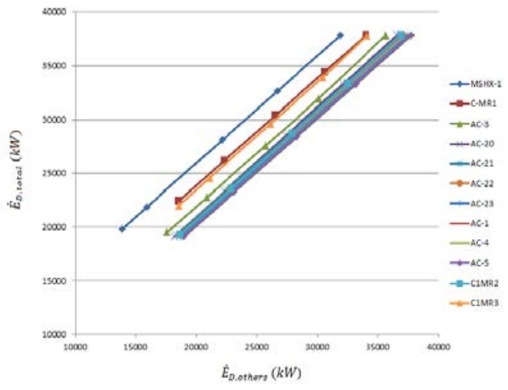

Fig. 3. Schematic of endogenous exergy destruction of various equipment

Figure 4 shows the advanced exergy analysis of the process equipment. The exergy destruction of the process equipment is divided into four categories of endogenous/ exogenous avoidable and endogenous/exogenous unavoidable and the values of each part are shown on the figure. In the MSHX1 exchanger, the unavailable exergy destruction is higher than the available section, while in other components, the available exergy destruction is higher than the unavailable exergy destruction. Also, except for AC1, AC4, AC5, AC20, and C1MR2, in other components, the endogenous exergy destruction is more than the exogenous exergy destruction, indicating that in these components, the largest source of irreversibility is the components not the interaction between components.

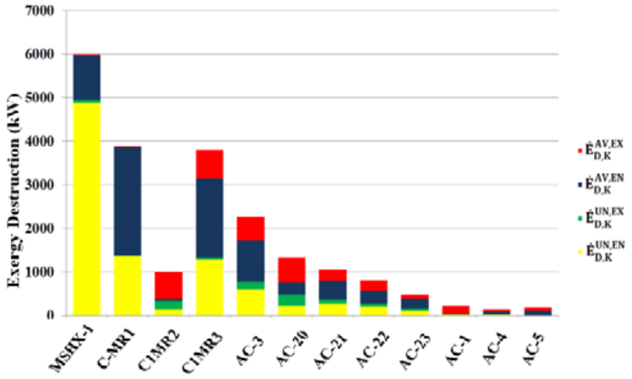

Fig. 4. Different parts of exergy destruction of process equipment

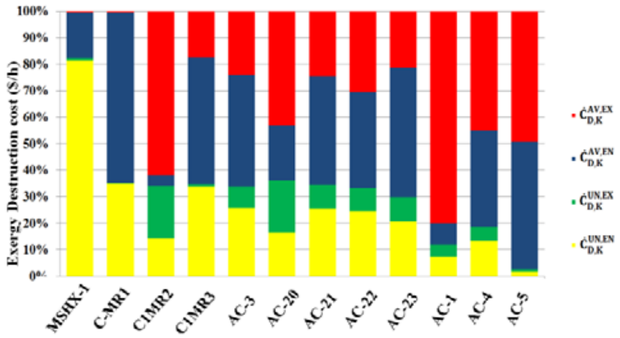

Fig. 5. Different parts of exergy destruction cost of process equipment

Figure 5 shows the cost analysis of exergy destruction of the examined equipment process. The cost of exergy destruction of the process equipment is divided into four categories of endogenous/exogenous avoidable and endogenous/exogenous unavoidable and the percentage effect of each part is specified on the figure.

In the MSHX1 heat exchanger, the cost of unavailable exergy destruction is more than the available exergy destruction, while in other components, the cost of available exergy destruction is higher than the unavailable exergy destruction.

Also, except for AC1, AC4, AC5, AC20, and C1MR2, in other components, the cost of endogenous exergy destruction is higher than the exogenous part. Meanwhile, in the MSHX1 exchanger, and the CMR1, C1MR3 compressors, since the cost of endogenous available exergy destruction is so much, the increased efficiency will have a major effect on reduced irreversibility and loss. In Figure 6, the analysis of advanced investment cost of process equipment is shown. The investment cost of the process equipment is divided into four categories of endogenous/exogenous avoidable and endogenous/ exogenous unavoidable, and percentage effect of each part is specified on the figure.

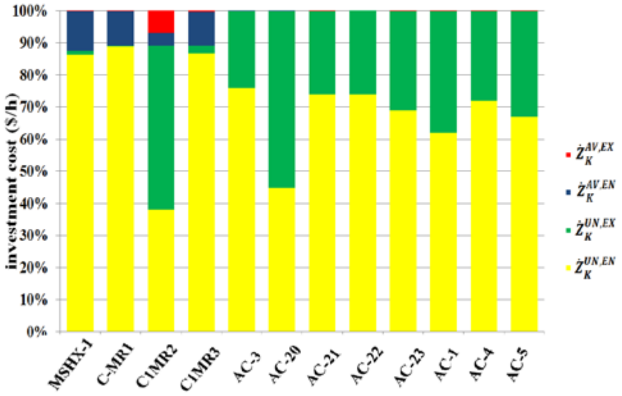

Fig. 6. Different parts of exergy destruction cost of process equipment

As can be seen, except for C1MR2 and AC20, where the investment cost of exogenous part is larger than endogenous part, in other equipment, the investment cost of endogenous part is larger than the exogenous part. In all the components of investment cost, the unavailable section is more than the available part. Meanwhile, since the endogenous available advanced investment cost in the MSHX1 exchanger and CMR1 and C1MR3 compressors are high, there is a good potential to improve the performance through the increased efficiency, and thereby, the investment cost can be reduced.

Three strategies are considered to reduce the available exergy destruction cost, the high available exergy destruction means that there is a good potential to improve system performance. As a result, the strategy (a) can be used in this case. The strategy (b) is used when the exogenous available exergy destruction cost is considerable compared to the endogenous available part. It should be noted that except for CMR1 and MSHX1, the other process equipment has this feature, and this strategy can be used for them. Finally, strategy (c) is used at a time when the exogenous available exergy destruction cost is significant, at least half of the total cost of available exergy destruction. As can be seen, for C1-MR2, AC20, AC1, AC4 and AC5 components, the strategy C can be used.

CONCLUSION

The advanced exergy and exergoeconomic analysis is carried out on the integrated process of LNG and NGL production.

The results of the process analysis are as follows:

❖ According to results of endogenous available exergy destruction cost, the MSHX1, CMR1 and C1MR3 have higher values than other equipment. The CMR1 heat exchanger has also the highest endogenous available exergy destruction, and the increased efficiency of this equipment will have a significant effect on reduction of this value.

❖ The results of the investment cost of endogenous available exergy destruction show that in this field, the MSHX1 heat exchanger and CMR1 and C1MR3 compressors have great potential to promote their performance by improving efficiency. It should be noted that among the equipment, the C1MR3 and CMR1 compressors have the highest investment cost of endogenous available exergy destruction. The examined air coolers also have the lowest investment cost of endogenous available exergy destruction.

❖ In general, and in accordance to the results of total cost of endogenous available exergy destruction, MSHX1 heat exchanger is in the priority to improve the performance.

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