*Iranian Journal of Oil & Gas Science and Technology*, Vol. 5 (2016), No. 3, pp. 45-61
http://ijogst.put.ac.ir

# Exergoeconomic Evaluation of LNG and NGL Co-production Process Based on the MFC Refrigeration Systems

**Hojat Ansarinasab[1], Mahmoud Afshar[2*], and Mehdi Mehrpooya[3]**

[1] M.S. Student, Department of Energy Systems Engineering, Petroleum University of Technology (PUT), Mahmoudabad, Iran
[2] Assistant Professor, Department of Energy Systems Engineering, Petroleum University of Technology (PUT), Mahmoudabad, Iran
[3] Assistant Professor, Renewable Energies and Environmental Department, Faculty of New Science and Technologies, University of Tehran, Iran

*Received:* May 23, 2015; *revised:* July 11, 2015; *accepted:* October 19, 2015

## Abstract

In this paper, exergy and exergoeconomic analysis is performed on the recently proposed process for the coproduction of liquefied natural gas (LNG) and natural gas liquids (NGL) based on the mixed fluid cascade (MFC) refrigeration systems, as one of the most important and popular natural gas liquefaction processes. To carry out this analysis, at first, the proposed process is simulated, and then the exergy analysis of the process equipment is performed; finally, an economic model is used for the exergoeconomic analysis. The results include cost of exergy destruction, exergoeconomic factor, exergy destruction, and exergy efficiency. The results of the exergy analysis demonstrate that the exergy efficiency of the proposed process is around 53.83%, and its total exergy destruction rate is 42617.5 kW at an LNG and NGL production rates of 68.99 kg/s and 27.41 kg/s respectively. The results of exergoeconomic analysis indicate that the maximum exergoeconomic factor, which is 69.53%, is related to the second compressor in the liquefaction cycle and the minimum exergoeconomic factor, which is 0.66%, is related to the fourth heat exchanger in the liquefaction cycle. In this process, demethanizer tower holds the highest relative cost difference (100.78) and the first air cooler in liquefaction cycle has the lowest relative cost difference (1.09). One of the most important exergoeconomic parameters is the cost of exergy destruction rate. The second heat exchanger has the highest exergy destruction cost (768.91 $/Gj) and the first air cooler in the liquefaction cycle has the lowest exergy destruction cost (19.36 $/Gj). Due to the high value of fuel cost rate (as defined in exergoeconomic analysis) in heat exchangers, their exergy destruction cost is much higher than other devices.

**Keywords:** Natural Gas, LNG, NGL, Exergy, Exergoeconomic

## 1. Introduction

Liquefied natural gas (LNG) is regarded as one of the convenient energy carriers, especially for transportation to very long distances; it is produced directly from the natural gas by the relevant refrigeration processes. Natural gas liquids (NGL), which is used as a main feed in petrochemical

* Corresponding Author:
Email: mafshar@put.ac.ir

processes (Elliot et al., 2005), is also produced by the relevant refrigeration system (Finn, 1999). LNG processes are classified by the refrigerant composition and the refrigeration system (Shukri, 2004). NGL and LNG production are performed in cryogenic processes in which the refrigeration system is a main part. Increasing the level of integration is a fundamental way for improving the efficiency and decreasing the operating and capital costs (Elliot et al., 2005). In this paper, the recently alternative integrated process for the cogeneration of LNG and NGL as proposed by (Mehrpooya et al., 2014) is investigated; specifically, an exergy analysis is performed to find the location, magnitude, and sources of inefficiencies in the proposed process.

The exergy analysis is used for the evaluation of LNG and NGL processes by many researchers. Exergy analysis was performed on four small-scale LNG processes and it was shown that the SMR process has the best exergy efficiency among four processes (Remeljeja and Hoadley, 2006). Vatani et al. (2014a) carried out energy and exergy analyses on five conventional LNG processes, and they concluded that the performance of the MFC process is considerable in terms of quality and quantity of energy consumption. Mehrpooya et al. (2006) performed exergy analysis on industrial refrigeration cycle used in NGL recovery units. Kanoglu (2002) presented the exergy analysis of cascade refrigeration cycle used for natural gas liquefaction. The exergetic efficiency of the multistage cascade refrigeration cycle is determined to be 38.5% indicating a great potential for improvements. Mafi (2009) carried out exergy analysis for multistage cascade low temperature refrigeration systems utilized in olefin plants. The exergy analysis results indicate that the major irreversibilities are due to losses within the compression system and driving forces across the heat exchangers. Morosuk et al. (2008) presented the exergy analysis of absorption refrigeration machines by a new method.

In exergy analysis, however, there is no term that directly treats costs associated with exergy destruction, which can only be determined by exergoeconomic analysis. PRICO liquefaction process exergy-based analyses, i.e. exergetic, exergoeconomic, and exergoenvironmental analyses, were performed by Morosuk et al. (2015). Ghorbani et al. (2012) carried out exergy and exergoeconomic analyses on natural gas separation process. The results show that the percentage increases in the unit exergoeconomic costs of the compression and the demethanizer section are the highest. The exergoeconomic analysis of an industrial refrigeration cycle was investigated by Mehrpooya et al. (2009), in which the impact of component inefficiencies on the fuel plant consumption, intrinsic, and induced malfunctions were analyzed and quantified. Siddiqui et al. (2014) presented exergoeconomic analysis on the refrigeration cycle in which the components of the cycle are compared based on the initial capital and the irreversibilities costs. Moreira et al. (2005) carried out exergoeconomic analysis for a double effect absorption refrigeration system with the direct combustion of the natural gas in which fixed capital investment for each subsystem of the unit was considered. Garousi Farshi et al. (2013) performed exergoeconomic analyses for combined ejector double effect and flow double effect systems in series to compare the influence of different operating parameters on investment product cost flow rates and costs of the overall systems.

In this article, exergy and exergoeconomic analyses are applied to recently alternatives integrated processes for the cogeneration of LNG and NGL with reasonable energy consumption and high ethane recovery. After the determination of high consuming and inefficient elements, a relationship between economic costs and investment is also proposed and the components with the highest cost of exergy destruction are identified.

## 2. Process description

The process flow diagram (PFD) of the mixed fluid cascade (MFC) integrated process is shown in

Figure 1. As seen, the NGL recovery and LNG production are carried out in an integrated process (Mehrpooya et al., 2014). A brief description is presented, and one may refer to the reference available for further details.

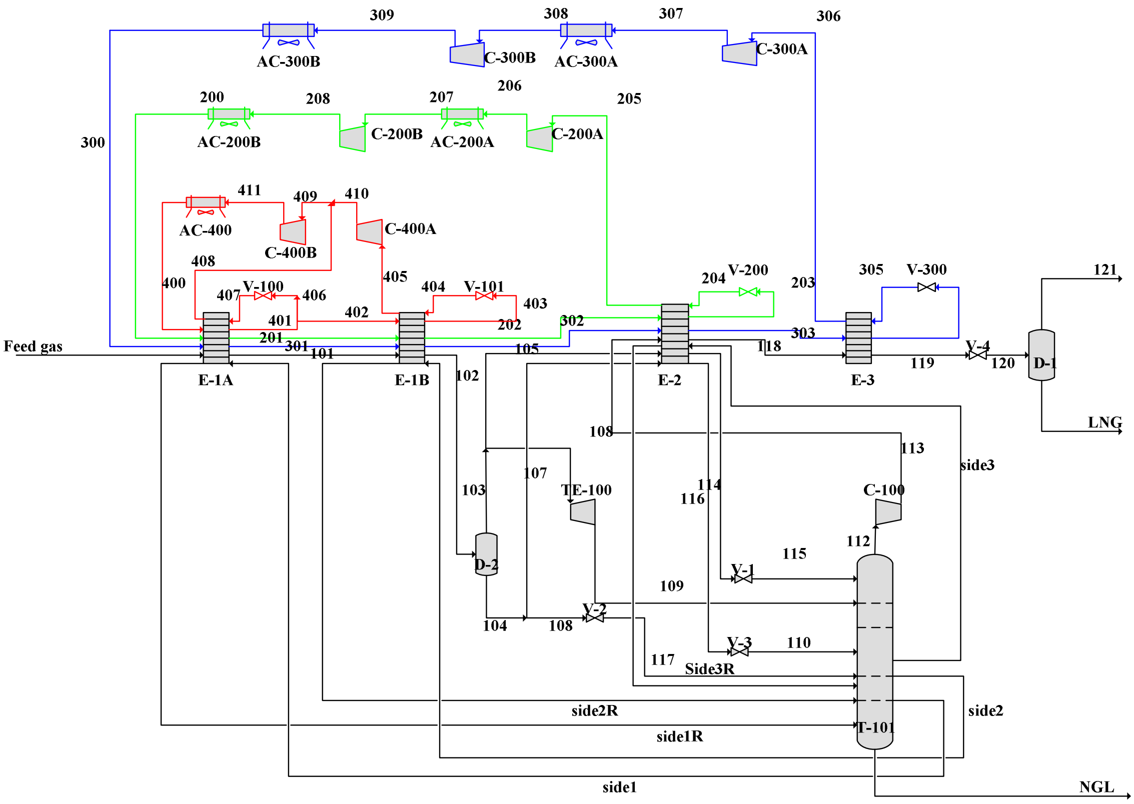


**Figure 1**
Process flow diagram of MFC configuration (Mehrpooya et al., 2014).

## 2.1. NGL recovery section

Cleaned and pretreated natural gas feed, with composition shown in Table 1, enters the plant at 37 °C and 63.09 bar, and is cooled in two steps: in the E-1A heat exchanger to 3 °C, and further to -30 °C in the second heat exchanger, E-1B. 40% of D-2 gas product is directed to the exchanger E-2 and is sub-cooled to about -88 °C (stream 114). Next, stream 114 is directed to the top of the demethanizer tower via a J-T valve as cold reflux. Another portion of the outlet vapor from D-2 is expanded thought a turbo expander prior to entering the demethanizer, right below the top section of the tower. Also, the liquid bottom is spilled into two parts: stream 108 is introduced to the column for fractionation through passing a J-T valve, and another portion, stream 107, is sub-cooled via E-2 to -30 °C and enters the tower through a J-T valve. Demethanizer tower operates at about 25 bar and contains conventional trays used in demethanizer columns. This tower has three liquid draw trays to provide the required heat for stripping volatile component from the produced NGL. The required heat is supplied by two multi-stream heat exchangers, E-1A and E-1B. Side streams 1, 2, and 3 enter the heat exchangers at 17.7, -7.9, and -54 °C and return to the tower at 35, 0, and -15 °C respectively. In this configuration, no reboiler is needed, and ethane recovery is enhanced to 92% (Mehrpooya et al., 2014).

## 2.2. Liquefaction section

Lean gas stream that leaves the demethanizer tower at about -97 °C and 25 bar enters the LNG section. Stream 112 is pressurized to about 63 bar in compressor C-100, and it is then cooled in E-2 to about -85.2 °C. In this process, final cooling in LNG production is performed in the E-3 heat exchanger, and the stream 119 is cooled to about -162.5 °C and delivered to the D-1 flash drum by passing a J-T valve. The liquid product of D-1 is LNG at atmospheric pressure (Mehrpooya et al., 2014).

**Table 1**
MFC configuration main streams data.

| | | Feed gas | Cycle 200 | Cycle 300 | Cycle 400 | NGL | LNG |
|---|---|---|---|---|---|---|---|
| **Composition** | methane | 83.00 | 10.76 | 40.00 | 0.00 | 0.68 | 98.82 |
| | ethane | 6.72 | 37.78 | 0.00 | 0.00 | 47.83 | 0.63 |
| | propane | 5.18 | 19.84 | 0.00 | 73.74 | 39.58 | 0.06 |
| | n-butane | 0.00 | 0.00 | 0.00 | 15.15 | 0.00 | 0.00 |
| | ethylene | 0.00 | 31.62 | 42.00 | 11.11 | 0.00 | 0.00 |
| | nitrogen | 0.50 | 0.00 | 18.00 | 0.00 | 0.00 | 0.41 |
| | Dioxide carbon | 0.20 | 0.00 | 0.00 | 0.00 | 1.08 | 0.07 |
| | $C^{4+}$ | 4.40 | 0.00 | 0.00 | 0.00 | 10.83 | 0.00 |
| **Operation Condition** | Temperature (°C) | 37.00 | 35.00 | 35.00 | 40.00 | 28.40 | -162.74 |
| | Pressure (bar) | 63.09 | 27.90 | 29.00 | 16.90 | 25.00 | 1.01 |
| | molar flow (kmol/hr) | 18000 | 19000 | 12500 | 27400 | 2404 | 15315 |

## 2.3. Refrigeration system

Because of the advantages of the mixed refrigerant systems, including its high thermal efficiency and high flexibility, it was used in the proposed integrated process (Mehrpooya et al., 2014).

### 2.3.1. The hottest cycle (cycle 400)

The process flow diagram of this cycle is shown in red lines in Figure 1. The first mixed refrigerant cycle provides the required refrigeration for precooling of the feed; it is also a heat sink for cooler cycles, cycles 200, and 300. The cycle 400 refrigerant is a mixture of propane and ethane. The refrigerant compositions are presented in Table 1.

### 2.3.2. The middle cycle (cycle 200)

This cycle, shown in green lines in Figure 1, provides a portion of the required refrigeration for the liquefaction section and the main portion of the required refrigeration for NGL recovery unit. Also, the middle cycle is a heat sink for the coldest cycle, i.e. cycle 300. The refrigerant in this cycle is composed of methane, ethane, propane, and ethylene.

### 2.3.3. Liquefaction cycle (cycle 300)

The main function of this cycle, shown in blue lines in Figure 1, is supplying the required refrigeration for liquefaction and sub-cooling. The refrigerant in this cycle is composed of methane, ethylene, and nitrogen. The thermodynamic data of the streams are shown in Table 2.

## 3. Process simulation

The simulation of the proposed integrated processes is carried out by Aspen HYSYS software, employing the Peng–Robinson–Stryjek–Vera (PRSV) equation of state. The main equipment power consumption in this process, specific energy consumption (SEC), and the coefficient of performance (COP) are presented in Table 3.

## 4. Exergy analysis

**Table 2**

Thermodynamic data for MFC configuration material streams.

| Stream no. | Temperature (°C) | Pressure (bar) | Flow (kmol/hr.) | Stream no. | Temperature (°C) | Pressure (bar) | Flow (kmol/hr.) |
|---|---|---|---|---|---|---|---|
| **feed** | 37.00 | 63.09 | 18000 | **300** | 35.00 | 29.00 | 12500 |
| **101** | 3.00 | 63.09 | 18000 | **301** | 3.00 | 29.00 | 12500 |
| **102** | -30.00 | 63.09 | 18000 | **302** | -27.00 | 29.00 | 12500 |
| **103** | -30.00 | 63.09 | 16550 | **303** | -85.20 | 29.00 | 12500 |
| **104** | -30.00 | 63.09 | 1449 | **304** | -159.00 | 29.00 | 12500 |
| **105** | -30.00 | 63.09 | 6620 | **305** | -166.85 | 3.50 | 12500 |
| **106** | -30.00 | 63.09 | 9930 | **306** | -89.56 | 3.50 | 12500 |
| **107** | -30.00 | 63.09 | 435 | **307** | 53.70 | 25.00 | 12500 |
| **108** | -30.00 | 63.09 | 1015 | **308** | 35.00 | 25.00 | 12500 |
| **109** | -65.13 | 26.00 | 9930 | **309** | 48.50 | 29.00 | 12500 |
| **110** | -62.86 | 25.00 | 435 | **400** | 40.00 | 16.90 | 27400 |
| **112** | -96.95 | 25.00 | 15595 | **401** | 8.80 | 16.90 | 27400 |
| **113** | -36.72 | 63.00 | 15595 | **402** | 8.80 | 16.90 | 10910 |
| **114** | -88.00 | 63.09 | 6620 | **403** | -22.00 | 16.90 | 10910 |
| **115** | -97.38 | 25.00 | 6620 | **404** | -29.38 | 3.00 | 10910 |
| **116** | -50.00 | 63.09 | 435 | **405** | 1.25 | 3.00 | 10910 |
| **117** | -47.88 | 25.50 | 1015 | **406** | 8.80 | 16.90 | 16490 |
| **118** | -85.20 | 63.00 | 15595 | **407** | -0.34 | 6.70 | 16490 |
| **119** | -162.50 | 63.00 | 15595 | **408** | 33.58 | 6.70 | 16490 |
| **120** | -162.74 | 1.01 | 15595 | **409** | 35.34 | 6.70 | 27400 |
| **121** | -162.74 | 1.01 | 280 | **410** | 37.99 | 6.70 | 10910 |
| **200** | 35.00 | 27.90 | 19000 | **411** | 81.86 | 16.90 | 27400 |
| **201** | 3.00 | 27.90 | 19000 | **side1** | 17.74 | 25.00 | 2300 |
| **202** | -27.00 | 27.90 | 19000 | **side2** | -7.88 | 25.00 | 2300 |
| **203** | -81.50 | 27.90 | 19000 | **side3** | -54.08 | 25.00 | 2300 |
| **204** | -90.99 | 3.10 | 19000 | **side1R** | 35.00 | 25.00 | 2300 |
| **205** | -29.72 | 3.10 | 19000 | **side2R** | 0.00 | 25.00 | 2300 |
| **206** | 67.63 | 15.00 | 19000 | **side3R** | -15.00 | 25.00 | 2300 |
| **207** | 35.00 | 15.00 | 19000 | **NGL** | 28.40 | 25.00 | 2404 |
| **208** | 77.90 | 27.90 | 19000 | **LNG** | -162.74 | 1.01 | 15315 |

In exergy analysis, the maximum useful work achievable by specific quantity of energy is calculated. Important parameters that are obtained from exergy analysis are exergy destruction, exergy efficiency, and exergy destruction ratio, as shown in the following expression (Bejan et al., 1996):

$$\dot{E}_D = \dot{E}_F - \dot{E}_P \tag{1}$$

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} \quad \text{or} \quad \varepsilon = 1 - \frac{\dot{E}_D}{\dot{E}_F} \tag{2}$$

$$y_D = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}} \tag{3}$$

where, $\dot{E}$ shows exergy rate, and subscripts *F*, *P*, *D*, and *k* denote the fuel, product, destruction, and component respectively. Also, the exergy data of the streams are shown in Table 4.

**Table 3**

Main equipment power consumption, specific energy consumption, and coefficient of performance.

| | Component Name | Power(kW)* |
|---|---|---|
| **Compressors** | C-100 | 6064.86 |
| | C-200A | 24107.69 |
| | C-200B | 10203.72 |
| | C-300A | 16807.21 |
| | C-300B | 1664.71 |
| | C-400A | 7123.01 |
| | C-400B | 21791.78 |
| **Turbo expander** | TE-100 | 2319.30 |
| **Air coolers** | AC-200A | 92.60 |
| | AC-200B | 1393.89 |
| | AC-300A | 299.75 |
| | AC-300B | 232.81 |
| | AC-400 | 4851.01 |
| **Specific energy (kWh/kg LNG)** | | 0.3572 |
| **COP** | | 2.218 |

* Mechanical efficiency =0.75

## 5. Exergoeconomic analysis

Exergoeconomic combines exergy analysis with the principles of economy to provide the information for designing a system, not possible through conventional energy analysis and economic evaluations.

### 5.1. Economic model

In the course of energy systems, economic analysis and optimization, annual investment, fuel cost, and systems maintenance cost must be calculated. In this research, total revenue requirement (TRR) method, as developed by the Electric Power Research Institute (EPRI, 1993), is used for the economic analysis of the system. In this method, all the costs, including return on investment, are also calculated; based on the hypotheses given in Table 5, equipment and fuel purchase prices, and the total revenue requirement are calculated annually. Finally, all the costs including maintenance and fuel costs during system operation would be balanced.

**Table 4**
Exergy and unit exergy cost for each stream of MFC configuration.

| Stream no. | $\dot{E}^{PH}$ (kW) | $\dot{E}^{CH}$ (kW) | $\dot{E}^{TOT}$ (kW) | $\dot{C}$ ($/hr) | c ($/Gj) | Stream no. | $\dot{E}^{PH}$ (kW) | $\dot{E}^{CH}$ (kW) | $\dot{E}^{TOT}$ (kW) | $\dot{C}$ ($/hr) | c ($/Gj) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **feed** | 48837 | 4947926 | 4996763 | 355201 | 19.74 | **300** | 28136 | 3146299 | 3174436 | 852985 | 74.64 |
| **101** | 49019 | 4947926 | 4996945 | 355361 | 19.75 | **301** | 28239 | 3146299 | 3174538 | 853076 | 74.65 |
| **102** | 50898 | 4947926 | 4998823 | 356224 | 19.79 | **302** | 28894 | 3146299 | 3175193 | 853376 | 74.66 |
| **103** | 46736 | 4262763 | 4309499 | 307106 | 19.79 | **303** | 39759 | 3146299 | 3186058 | 856681 | 74.69 |
| **104** | 3599 | 685725 | 689324 | 49123 | 19.79 | **304** | 59385 | 3146299 | 3205684 | 862276 | 74.72 |
| **105** | 18694 | 1705105 | 1723800 | 122842 | 19.79 | **305** | 58069 | 3146299 | 3204369 | 862276 | 74.75 |
| **106** | 28041 | 2557658 | 2585699 | 184263 | 19.79 | **306** | 14336 | 3146299 | 3160635 | 850508 | 74.75 |
| **107** | 1080 | 205717 | 206797 | 14737 | 19.79 | **307** | 27132 | 3146299 | 3173431 | 852669 | 74.64 |
| **108** | 2519 | 480008 | 482527 | 34386 | 19.79 | **308** | 26966 | 3146299 | 3173265 | 852704 | 74.64 |
| **109** | 24605 | 2557658 | 2582263 | 184019 | 19.79 | **309** | 28243 | 3146299 | 3174542 | 852955 | 74.64 |
| **110** | 1083 | 205718 | 206801 | 14755 | 19.82 | **400** | 40799 | 16532598 | 16573397 | 6225893 | 104.35 |
| **112** | 40443 | 3621054 | 3661497 | 262010 | 19.88 | **401** | 40519 | 16532598 | 16573117 | 6225647 | 104.35 |
| **113** | 44571 | 3621054 | 3665625 | 262834 | 19.92 | **402** | 16134 | 6582870 | 6599004 | 2478898 | 104.35 |
| **114** | 23729 | 1705105 | 1728834 | 124374 | 19.98 | **403** | 17366 | 6582870 | 6600236 | 2479464 | 104.35 |
| **115** | 23114 | 1705105 | 1728219 | 124374 | 19.99 | **404** | 16918 | 6582870 | 6599788 | 2479464 | 104.36 |
| **116** | 1140 | 205717 | 206857 | 14756 | 19.81 | **405** | 8128 | 6582870 | 6590999 | 2476162 | 104.36 |
| **117** | 2346 | 480008 | 482354 | 34386 | 19.80 | **406** | 24385 | 9949728 | 9974113 | 3746749 | 104.35 |
| **118** | 54931 | 3621054 | 3675985 | 265985 | 20.10 | **407** | 23850 | 9949728 | 9973578 | 3746749 | 104.35 |
| **119** | 76598 | 3621054 | 3697653 | 272163 | 20.45 | **408** | 20385 | 9949728 | 9970113 | 3745447 | 104.35 |
| **120** | 74191 | 3621054 | 3695246 | 272163 | 20.46 | **409** | 33905 | 16532598 | 16566503 | 6222568 | 104.34 |
| **121** | 281 | 58726 | 59006 | 4346 | 20.46 | **410** | 13525 | 6582870 | 6596395 | 2477121 | 104.31 |
| **200** | 40366 | 8003347 | 8043713 | 2264895 | 78.21 | **411** | 51073 | 16532598 | 16583671 | 6225338 | 104.27 |
| **201** | 41870 | 8003347 | 8045217 | 2266218 | 78.25 | **side1** | 4308 | 1184086 | 1188394 | 446441 | 104.35 |
| **202** | 46445 | 8003347 | 8049792 | 2268319 | 78.27 | **side2** | 4683 | 1133586 | 1138270 | 427635 | 104.36 |
| **203** | 55031 | 8003347 | 8058378 | 2270931 | 78.28 | **side3** | 5863 | 1031562 | 1037425 | 389749 | 104.36 |
| **204** | 53551 | 8003347 | 8056898 | 2270931 | 78.29 | **side1R** | 4331 | 1184020 | 1188352 | 446425 | 104.35 |
| **205** | 15917 | 8003347 | 8019264 | 2260323 | 78.29 | **side2R** | 4587 | 1133253 | 1137840 | 427473 | 104.36 |
| **206** | 34600 | 8003347 | 8037947 | 2263374 | 78.22 | **side3R** | 4970 | 1031491 | 1036461 | 389386 | 104.36 |
| **207** | 33767 | 8003347 | 8037115 | 2263389 | 78.23 | **NGL** | 4158 | 1330829 | 1334987 | 95529 | 19.88 |
| **208** | 41782 | 8003347 | 8045129 | 2264734 | 78.19 | **LNG** | 73870 | 3562369 | 3636239 | 267820 | 20.46 |

## 5.2. Levelized costs

With an increase in the system operating years, investment related costs decreases, while fuel costs increase. Therefore, the balanced amount of annual total revenue requirement ($TRR_L$) is calculated by the capital return factor (CRF) and a decrease of money value as given in Equation 4 (Bejan et al., 1996):

$$TRR_L = CRF\sum_{1}^{BL}\frac{TRR_j}{(1+i_{eff})^j} \quad (4)$$

where, $TRR_j$ is the total revenue requirement in *j*th year of system operation, and BL denotes economic life cycle of the system as measured in years; $i_{eff}$ stands for the average annual rate of effective devaluation. Capital recovery factor (CRF) is calculated as follows:

$$CRF = \frac{i_{eff}(1+i_{eff})^{BL}}{(1+i_{eff})^{BL}-1} \quad (5)$$

In this study, the value for $TRR_j$ is the sum of four annual values, including minimum return on investment (ROI), total capital recovery (TCR), operation and maintenance costs (OMC), and fuel costs (FC).

**Table 5**

Economic constants and assumptions.

| Economic parameters | Value |
|---|---|
| Average annual rate of the cost of money ($i_{eff}$) | 10% |
| Average nominal escalation rate for the operating and maintenance cost ($r_{OMC}$) | 5% |
| Average nominal escalation rate for fuel ($r_{FC}$) | 5% |
| Plant economic life (book life) | 25 years |
| Total annual operating hours of the system operation at full load | 7300 |

More details on the general procedure, definitions, and calculations are presented elsewhere (Bejan et al., 1996):

$$TRR_j = TCR_j + ROI_j + FC_j + OMC_j \quad (6)$$

Fuel cost for this system (as defined in exergoeconomic analysis) is the electricity cost which is calculated for the first year of operation as follows:

$$FC_0 = c_w \times \dot{W} \times \tau \quad (7)$$

where, τ is operating hours of the system per year (7300 hrs) and $\dot{W}$ is the compressor power (kW); $c_w$ is a constant related to the electricity cost. Then, the levelized value of $FC_L$ for the series is calculated by multiplying the fuel cost at the beginning of the first year of operation by the constant-escalation levelization factor (CELF):

$$FC_L = FC_0 \times CELF = FC_0\frac{k_{FC}(1-k_{FC}^{BL})}{(1-k_{FC})}CRF \quad (8)$$

where,

$$k_{FC} = \frac{1+r_{FC}}{1+i_{iff}} \qquad r_{FC} = \text{constant} \quad (9)$$

where, $r_{FC}$ and CRF are annual escalation rate of fuel cost and capital recovery factor respectively. Similarly, the levelized annual operation and maintenance cost ($OMC_L$) is obtained by the following equation:

$$OMC_L = OMC_0 \times CELF = OMC_0 \frac{k_{OMC}(1-k_{OMC}^{BL})}{(1-k_{OMC})} CRF \tag{10}$$

where,

$$k_{OMC} = \frac{1+r_{OMC}}{1+i_{iff}} \qquad r_{OMC} = \text{constant} \tag{11}$$

where, $r_{OMC}$ is the nominal escalation rate of operation and maintenance costs. Finally, the levelized carrying charge ($CC_L$) is obtained by the following relation:

$$CC_L = TRR_L - FC_L - OMC_L \tag{12}$$

where, $\dot{Z}$ shows the cost rate associated with the capital investment and operating and maintenance costs:

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} = \frac{CC_L + OMC_L}{\tau} \frac{PEC_k}{\sum_k PEC_k} \tag{13}$$

where, $\tau$ and $PEC_k$ denote the total annual time (hours) of system operation at full load and the purchased-equipment cost of the *k*th system component respectively. The equations for estimating cost of the equipment is shown in Table 6 and the results calculated are shown in and Table 7.

**Table 6**
Equation of cost of the process unit.

| **Component** | **Purchased equipment cost functions** |
|---|---|
| **Compressor** | $C_C=7.90(HP)^{0.62}$ [43]<br>$C_C$= Cost of Compressor (k$) |
| **Heat exchanger** | $C=1.218*f_d f_m f_p C_b$<br>$C_b=\exp[8.821-0.30863(\ln A)+0.0681(\ln A)^2]$, $150<A<12000$,<br>fd=exp(-1.1156+0.0906*(ln(A))), $f_M$= Material Factor, $f_P$=Pressure Factor |
| **Separator** | C=1.218[a+bW], K$ $5<W<40$ tons/hr<br>a= 42, b=1.63 |
| **Air cooler** | $C_{AC}=1.218 f_m f_P \exp[a+b\ln Q+c(\ln Q)^2]$, Q in KSCFM [43]<br>$C_{AC}$= Cost of Air cooler (k$)<br>$f_m$=Material Factor, $f_P$=Pressure Factor, a=0.4692, b=0.1203, c=0.0931 |
| **Turbo Expander** | $C_{TE}=0.378(HP)^{0.81}$ [43]<br>$C_{TE}$= Cost of Turbo Expander (k$) |
| **Absorption** | $C_T=1.218[f_1C_b+Nf_2f_3f_4C_t+C_{p1}]$<br>$C_t$ =457.7 exp (0.1739D), $2<D<16$ ft tray diameter, N=number of trays<br>$C_b=1.218\exp[6.629+0.1826(\ln W)+0.02297(\ln W)^2]$, $4250<W<980{,}000$ lb shell<br>$C_{p1}=300D^{0.7396}L^{0.7068}$, $3<D<21$, $27<L<40$ ft (platforms and ladders)<br>$f_1$= Material Factor, $f_2$= 1.189+0.0577D, $f_3$=Tray Types Factor, $f_4=2.25/(1.0414)^N$ |

## 5.3. Cost balance equations

To calculate the unit cost of exergy for each stream, exergy balance equations are written for each component as follows:

$$\sum_i (c_i \dot{E}_i)_k + \dot{Z}_k^{CI} + \dot{Z}_k^{OM} = \sum_o (c_o \dot{E}_o)_k \quad (14)$$

For some of the equipment with more than one output flow, there is more than one unknown parameter, so auxiliary equations based on the laws of *P* and *F* (Lazzaretto and Tsatsaronis, 1997) for these equipment are defined. Tables 8 and 9 respectively show the cost balance and auxiliary equations for a system. Considering that, for some of the components, equations cannot be solved independently; there is a set of linear dependent equations that should be solved simultaneously. A computer program is developed in the MATLAB for solving the cost balance and auxiliary equations to obtain the unit exergy cost for each flow, as presented in Table 4.

**Table 7**

Purchased equipment and investment costs for MFC process components.

| | **PEC ($)** | **$\dot{Z}^{CI}$ ($/hr)** | **$\dot{Z}^{OM}$ ($/hr)** | **$\dot{Z}$ ($/hr)** |
|---|---|---|---|---|
| **E-1A** | 123171.36 | 8.01 | 0.20 | 8.21 |
| **E-1B** | 79843.06 | 5.19 | 0.13 | 5.32 |
| **E-2** | 127701.63 | 8.30 | 0.21 | 8.51 |
| **E-3** | 65857.68 | 4.28 | 0.11 | 4.39 |
| **AC-200A** | 56774.85 | 3.69 | 0.09 | 3.78 |
| **AC-200B** | 56774.85 | 3.69 | 0.09 | 3.78 |
| **AC-300A** | 24819.81 | 1.61 | 0.04 | 1.65 |
| **AC-300B** | 56774.85 | 3.69 | 0.09 | 3.78 |
| **AC-400** | 103729.52 | 6.74 | 0.17 | 6.91 |
| **C-100** | 2098886.04 | 136.44 | 3.46 | 139.90 |
| **C-200A** | 4938254.48 | 321.01 | 8.14 | 329.15 |
| **C-200B** | 2897793.17 | 188.37 | 4.78 | 193.15 |
| **C-300A** | 3948609.45 | 256.68 | 6.51 | 263.19 |
| **C-300B** | 941603.69 | 61.21 | 1.55 | 62.76 |
| **C-400A** | 2318935.48 | 150.74 | 3.82 | 154.56 |
| **C-400B** | 4654001.65 | 302.53 | 7.67 | 310.20 |
| **TE-100** | 255051.40 | 16.58 | 0.42 | 17.00 |
| **D-1** | 55387.15 | 3.60 | 0.09 | 3.69 |
| **D-2** | 74983.07 | 4.87 | 0.12 | 4.99 |
| **T-101** | 77848.47 | 5.06 | 0.13 | 5.19 |

**Table 8**
Main equations for MFC process.

| Equipment | Main Equation |
|---|---|
| **E-1A** | $\dot{C}_{300}+\dot{C}_{200}+\dot{C}_{400}+\dot{C}_{407}+\dot{C}_{\text{feed}}+\dot{C}_{\text{side1}}+\dot{Z}_{\text{E-1A}}=\dot{C}_{301}+\dot{C}_{201}+\dot{C}_{401}+\dot{C}_{101}+\dot{C}_{408}+\dot{C}_{\text{side1R}}$ |
| **E-1B** | $\dot{C}_{101}+\dot{C}_{301}+\dot{C}_{201}+\dot{C}_{402}+\dot{C}_{404}+\dot{C}_{\text{side2}}+\dot{C}_{\text{side3}}+\dot{Z}_{\text{E-1B}}=\dot{C}_{102}+\dot{C}_{302}+\dot{C}_{202}+\dot{C}_{403}+\dot{C}_{405}+\dot{C}_{\text{side2R}}+\dot{C}_{\text{side3R}}$ |
| **E-2** | $\dot{C}_{113}+\dot{C}_{302}+\dot{C}_{202}+\dot{C}_{204}+\dot{C}_{107}+\dot{C}_{105}+\dot{Z}_{\text{E-2}}=\dot{C}_{118}+\dot{C}_{303}+\dot{C}_{203}+\dot{C}_{205}+\dot{C}_{114}+\dot{C}_{116}$ |
| **E-3** | $\dot{C}_{303}+\dot{C}_{305}+\dot{C}_{118}+\dot{Z}_{\text{E-3}}=\dot{C}_{304}+\dot{C}_{306}+\dot{C}_{119}$ |
| **V-1** | $\dot{C}_{114}=\dot{C}_{115}$ |
| **V-2** | $\dot{C}_{108}=\dot{C}_{117}$ |
| **V-3** | $\dot{C}_{110}=\dot{C}_{116}$ |
| **V-4** | $\dot{C}_{119}=\dot{C}_{120}$ |
| **V-100** | $\dot{C}_{406}=\dot{C}_{407}$ |
| **V-101** | $\dot{C}_{403}=\dot{C}_{404}$ |
| **V-200** | $\dot{C}_{203}=\dot{C}_{204}$ |
| **V-300** | $\dot{C}_{304}=\dot{C}_{305}$ |
| **C-100** | $\dot{C}_{112}+\dot{C}_{W}+\dot{Z}_{\text{C-100}}=\dot{C}_{113}$ |
| **C-200A** | $\dot{C}_{205}+\dot{C}_{W}+\dot{Z}_{\text{C-200A}}=\dot{C}_{206}$ |
| **C-200B** | $\dot{C}_{207}+\dot{C}_{W}+\dot{Z}_{\text{C-200B}}=\dot{C}_{208}$ |
| **C-300A** | $\dot{C}_{306}+\dot{C}_{W}+\dot{Z}_{\text{C-300A}}=\dot{C}_{307}$ |
| **C-300B** | $\dot{C}_{308}+\dot{C}_{W}+\dot{Z}_{\text{C-300B}}=\dot{C}_{309}$ |
| **C-400A** | $\dot{C}_{405}+\dot{C}_{W}+\dot{Z}_{\text{C-400A}}=\dot{C}_{410}$ |
| **C-400B** | $\dot{C}_{409}+\dot{C}_{W}+\dot{Z}_{\text{C-400B}}=\dot{C}_{411}$ |
| **TE-100** | $\dot{C}_{106}-\dot{C}_{W}+\dot{Z}_{\text{TE-100}}=\dot{C}_{109}$ |
| **AC-200A** | $\dot{C}_{206}+\dot{C}_{W}+\dot{Z}_{\text{AC-200A}}=\dot{C}_{207}$ |
| **AC-200B** | $\dot{C}_{208}+\dot{C}_{W}+\dot{Z}_{\text{AC-200B}}=\dot{C}_{200}$ |
| **AC-300A** | $\dot{C}_{307}+\dot{C}_{W}+\dot{Z}_{\text{AC-300A}}=\dot{C}_{308}$ |
| **AC-300B** | $\dot{C}_{309}+\dot{C}_{W}+\dot{Z}_{\text{AC-300B}}=\dot{C}_{300}$ |
| **AC-400** | $\dot{C}_{411}+\dot{C}_{W}+\dot{Z}_{\text{AC-400}}=\dot{C}_{400}$ |
| **D-1** | $\dot{C}_{120}+\dot{Z}_{\text{D-1}}=\dot{C}_{121}+\dot{C}_{\text{LNG}}$ |
| **D-2** | $\dot{C}_{102}+\dot{Z}_{\text{D-2}}=\dot{C}_{103}+\dot{C}_{104}$ |
| **TEE-100** | $\dot{C}_{103}=\dot{C}_{105}+\dot{C}_{106}$ |
| **TEE-101** | $\dot{C}_{104}=\dot{C}_{107}+\dot{C}_{108}$ |
| **TEE-102** | $\dot{C}_{401}=\dot{C}_{402}+\dot{C}_{406}$ |
| **MIX-1** | $\dot{C}_{408}+\dot{C}_{410}=\dot{C}_{409}$ |
| **T-101** | $\dot{C}_{115}+\dot{C}_{117}+\dot{C}_{109}+\dot{C}_{110}+\dot{C}_{\text{side1R}}+\dot{C}_{\text{side2R}}+\dot{C}_{\text{side3R}}+\dot{Z}_{\text{T-101}}=\dot{C}_{112}+\dot{C}_{\text{side1}}+\dot{C}_{\text{side2}}+\dot{C}_{\text{side3}}+\dot{C}_{\text{NGL}}$ |

**Table 9**
Auxiliary equations for MFC process.

| Equipment | Auxiliary Equation |
|---|---|
| **E-1A** | $\frac{\dot{C}_{407}}{\dot{E}_{407}}=\frac{\dot{C}_{408}}{\dot{E}_{408}},\frac{\dot{C}_{\text{side1}}}{\dot{E}_{\text{side1}}}=\frac{\dot{C}_{\text{side1R}}}{\dot{E}_{\text{side1R}}},\frac{\dot{C}_{101}-\dot{C}_{\text{feed}}}{\dot{E}_{101}-\dot{E}_{\text{feed}}}=\frac{\dot{C}_{201}-\dot{C}_{200}}{\dot{E}_{201}-\dot{E}_{200}}=\frac{\dot{C}_{301}-\dot{C}_{300}}{\dot{E}_{301}-\dot{E}_{300}}=\frac{\dot{C}_{401}-\dot{C}_{400}}{\dot{E}_{401}-\dot{E}_{400}}$ |
| **E-1B** | $\frac{\dot{C}_{\text{side2}}}{\dot{E}_{\text{side2}}}=\frac{\dot{C}_{\text{side2R}}}{\dot{E}_{\text{side2R}}},\frac{\dot{C}_{\text{side3}}}{\dot{E}_{\text{side3}}}=\frac{\dot{C}_{\text{side3R}}}{\dot{E}_{\text{side3R}}},\frac{\dot{C}_{404}}{\dot{E}_{404}}=\frac{\dot{C}_{405}}{\dot{E}_{405}},\frac{\dot{C}_{102}-\dot{C}_{101}}{\dot{E}_{102}-\dot{E}_{101}}=\frac{\dot{C}_{202}-\dot{C}_{201}}{\dot{E}_{202}-\dot{E}_{201}}=\frac{\dot{C}_{302}-\dot{C}_{301}}{\dot{E}_{302}-\dot{E}_{301}}=\frac{\dot{C}_{403}-\dot{C}_{402}}{\dot{E}_{403}-\dot{E}_{402}}$ |
| **E-2** | $\frac{\dot{C}_{204}}{\dot{E}_{204}}=\frac{\dot{C}_{205}}{\dot{E}_{205}},\frac{\dot{C}_{118}-\dot{C}_{113}}{\dot{E}_{118}-\dot{E}_{113}}=\frac{\dot{C}_{116}-\dot{C}_{107}}{\dot{E}_{116}-\dot{E}_{107}}=\frac{\dot{C}_{114}-\dot{C}_{105}}{\dot{E}_{114}-\dot{E}_{105}}=\frac{\dot{C}_{203}-\dot{C}_{202}}{\dot{E}_{203}-\dot{E}_{202}}=\frac{\dot{C}_{303}-\dot{C}_{302}}{\dot{E}_{303}-\dot{E}_{302}}$ |
| **E-3** | $\frac{\dot{C}_{305}}{\dot{E}_{305}}=\frac{\dot{C}_{306}}{\dot{E}_{306}},\frac{\dot{C}_{119}-\dot{C}_{118}}{\dot{E}_{119}-\dot{E}_{118}}=\frac{\dot{C}_{304}-\dot{C}_{303}}{\dot{E}_{304}-\dot{E}_{303}}$ |
| **TE-100** | $\frac{\dot{C}_{106}}{\dot{E}_{106}}=\frac{\dot{C}_{109}}{\dot{E}_{109}}$ |
| **D-1** | $\frac{\dot{C}_{121}}{\dot{E}_{121}}=\frac{\dot{C}_{\text{LNG}}}{\dot{E}_{\text{LNG}}}$ |
| **D-2** | $\frac{\dot{C}_{103}}{\dot{E}_{103}}=\frac{\dot{C}_{104}}{\dot{E}_{104}}$ |
| **TEE-100** | $\frac{\dot{C}_{105}}{\dot{E}_{105}}=\frac{\dot{C}_{106}}{\dot{E}_{106}}$ |
| **TEE-101** | $\frac{\dot{C}_{107}}{\dot{E}_{107}}=\frac{\dot{C}_{108}}{\dot{E}_{108}}$ |
| **TEE-102** | $\frac{\dot{C}_{402}}{\dot{E}_{402}}=\frac{\dot{C}_{406}}{\dot{E}_{406}}$ |
| **T-101** | $\frac{\dot{C}_{407}}{\dot{E}_{407}}=\frac{\dot{C}_{\text{side1}}}{\dot{E}_{\text{side1}}},\frac{\dot{C}_{404}}{\dot{E}_{404}}=\frac{\dot{C}_{\text{side2}}}{\dot{E}_{\text{side2}}}=\frac{\dot{C}_{\text{side3}}}{\dot{E}_{\text{side3}}},\frac{\dot{C}_{112}}{\dot{E}_{112}}=\frac{\dot{C}_{\text{NGL}}}{\dot{E}_{\text{NGL}}}$ |

## 5.4. Exergoeconomic variables

As we define one fuel and production for every system components in exergy analysis, cost flow rate related to fuel ($\dot{C}_F$) and production ($\dot{C}_P$) of a component can be obtained similar to exergy flow rate of $\dot{E}_F$ and $\dot{E}_P$. Average fuel cost for *k*th element of a system ($c_{F,k}$) shows the average cost by which unit fuel exergy for the *k*th element is supplied:

$$c_{F,k}=\frac{\dot{C}_{F,k}}{\dot{E}_{F,k}} \tag{15}$$

Unit product cost ($c_{p,k}$) is defined as the average cost by which unit exergy for the product of the *k*th element is provided:

$$c_{P,k}=\frac{\dot{C}_{P,k}}{\dot{E}_{P,k}} \tag{16}$$

Cost of exergy destruction for the *k*th element in the system, which is related to exergy destruction ($\dot{E}_{D,k}$), is considered a hidden cost which can only be revealed by an exergoeconomic analysis:

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \tag{17}$$

Relative cost difference between the average cost per exergy unit of product and fuel is given by:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} = \frac{1-\varepsilon_k}{\varepsilon_k} + \frac{\dot{Z}_k}{c_{F,k}\dot{E}_{P,k}} \tag{18}$$

Exergoeconomic factor indicates the ratio of investments cost to investment and exergy destruction costs as follows:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \tag{19}$$

## 6. Results and discussion

### 6.1. Exergy analysis

In this paper, exergy and exergoeconomic analyses are applied to the recently alternatives integrated processes for the cogeneration of LNG and NGL. The exergy analysis of this process results are presented in Table 10. In this process, the highest irreversibility is related to the compressor C-200A, with a value of 5423 kW, and the second highest value was related to units C-400B, C-300A, and E-2 respectively. Exergy efficiency for expansion valves was lower than the other units. The exergy efficiency of this process is around 53.83%, and its total exergy destruction rate is equal to 42617.5 kW.

**Table 10**
Exergy efficiency and exergy destruction of MFC process.

| Component | $\dot{E}_D$ (kW) | ε (%) | Component | $\dot{E}_D$ (kW) | ε (%) |
|---|---|---|---|---|---|
| **C-100** | 1937.11 | 68.06 | **E-1A** | 1934.46 | 97.77 |
| **C-200A** | 5423.14 | 77.50 | **E-1B** | 1438.37 | 97.73 |
| **C-200B** | 2188.88 | 78.55 | **E-2** | 2727.97 | 96.84 |
| **C-300A** | 4010.81 | 76.14 | **E-3** | 2439.32 | 94.31 |
| **C-300B** | 387.46 | 76.72 | **V-1** | 615.25 | 54.00 |
| **C-400A** | 1726.58 | 75.76 | **V-2** | 172.76 | 53.00 |
| **C-400B** | 4623.88 | 78.78 | **V-3** | 56.16 | 69.00 |
| **TE-100** | 1117.28 | 67.49 | **V-4** | 2406.98 | 31.00 |
| **AC-200A** | 693.85 | 98.00 | **V-100** | 534.65 | 30.00 |
| **AC-200B** | 835.19 | 98.00 | **V-101** | 447.51 | 40.00 |
| **AC-300A** | 272.65 | 99.00 | **V-200** | 1480.35 | 90.00 |
| **AC-300B** | 283.69 | 99.00 | **V-300** | 1315.85 | 86.00 |
| **AC-400** | 1825.99 | 96.00 | **MIX-1** | 4.77 | 100.00 |
| **T-101** | 1716.58 | 50.01 | | | |

### 6.2. Exergoeconomic analysis

By exergoeconomic analysis, a rational relationship between initial investment and current costs, due to failures, can be established, which enables us to determine whether a system works economically or not. In this method, the investment costs are estimated first, as shown in Table 7, and then, using total revenue requirement method and writing cost balance equation, exergy unit cost for every stream is determined (Table 4). Finally, the exergoeconomic factor and relative cost difference are determined by exergoeconomic analysis and the results are shown in Tables 11. The exergoeconomic factor value shows information about the investment cost and exergy efficiency of a system: large values indicates that in order to decrease the system cost, elements costs must be reduced, while small values indicates that in order to reduce the system cost, the performance and efficiency of a system must be improved.

**Table 11**

The results of exergy and exergoeconomic analysis of MFC process.

| Component | $\dot{E}_D$ (kW) | $C_F$ ($/Gj) | $C_P$ ($/Gj) | $\dot{C}_D$ ($/hr) | $\dot{Z}$ ($/hr) | $\varepsilon$ (%) | $Y_D$ (%) | $r$ (%) | $f$ (%) |
|---|---|---|---|---|---|---|---|---|---|
| **C-100** | 1937.11 | 19.72 | 38.39 | 137.52 | 139.90 | 68.06 | 2.10 | 94.67 | 50.43 |
| **C-200A** | 5423.14 | 19.72 | 30.34 | 384.99 | 329.15 | 77.50 | 5.87 | 53.84 | 46.09 |
| **C-200B** | 2188.88 | 19.72 | 31.80 | 155.39 | 193.15 | 78.55 | 2.37 | 61.26 | 55.42 |
| **C-300A** | 4010.81 | 19.72 | 31.61 | 284.74 | 263.19 | 76.14 | 4.34 | 60.31 | 48.03 |
| **C-300B** | 387.46 | 19.72 | 39.35 | 27.50 | 62.76 | 76.72 | 0.42 | 99.55 | 69.53 |
| **C-400A** | 1726.58 | 19.72 | 33.99 | 122.57 | 154.56 | 75.76 | 1.87 | 72.34 | 55.77 |
| **C-400B** | 4623.88 | 19.72 | 30.05 | 328.26 | 310.20 | 78.78 | 5.01 | 52.38 | 48.58 |
| **TE-100** | 1117.28 | 11.93 | 19.72 | 48.00 | 17.00 | 67.49 | 1.21 | 65.23 | 26.15 |
| **AC-200A** | 693.85 | 19.72 | 20.15 | 49.26 | 3.78 | 98.00 | 0.75 | 2.20 | 7.13 |
| **AC-200B** | 835.19 | 19.72 | 20.15 | 59.29 | 3.78 | 98.00 | 0.90 | 2.17 | 5.99 |
| **AC-300A** | 272.65 | 19.72 | 19.94 | 19.36 | 1.65 | 99.00 | 0.29 | 1.09 | 7.85 |
| **AC-300B** | 283.69 | 19.72 | 19.96 | 20.14 | 3.78 | 99.00 | 0.31 | 1.20 | 15.80 |
| **AC-400** | 1825.99 | 19.72 | 20.58 | 129.63 | 6.91 | 96.00 | 1.98 | 4.39 | 5.06 |
| **E-1A** | 1934.46 | 104.35 | 106.75 | 726.71 | 8.21 | 97.77 | 2.09 | 2.30 | 1.12 |
| **E-1B** | 1438.37 | 104.36 | 106.81 | 540.38 | 5.32 | 97.73 | 1.56 | 2.35 | 0.97 |
| **E-2** | 2727.97 | 78.29 | 80.88 | 768.91 | 8.51 | 96.84 | 2.96 | 3.30 | 1.09 |
| **E-3** | 2439.32 | 74.75 | 79.29 | 656.41 | 4.39 | 94.31 | 2.64 | 6.07 | 0.66 |
| **T-101** | 1716.58 | 104.35 | 209.51 | 644.85 | 5.19 | 50.01 | 1.86 | 100.78 | 0.80 |

The results for this process demonstrate that C-300B compressor has the highest exergoeconomic factor (69.53) and the smallest exergoeconomic factor is related to E-3 heat exchanger (0.66). The relative cost difference is an indication of relative increase in the exergy cost of product with respect to the exergy cost of fuel in an element which plays a significant role in the evaluation and optimization of the system. In this process, T-101 demethanizer tower holds the highest relative cost difference (100.78) and AC-300A air cooler has the lowest relative cost difference (1.09).

The magnitudes of exergy cost of fuel and product determines the cost of exergy rate in an element. The maximum fuel cost rate is related to E-1B heat exchanger with a value of 104.36 $/Gj, while the maximum product cost rate is related to T-101 demethanizer tower with a value of 209.51 $/Gj. One of the most important exergoeconomic parameters is the cost of exergy destruction rate; E-2 heat exchanger has the highest exergy destruction cost (768.91 $/Gj) and AC-300A air cooler has the lowest exergy destruction cost (19.36 $/Gj).

## 8. Conclusions

In this paper, exergy and exergoeconomic analyses are applied to the recently alternative integrated processes for the cogeneration of LNG and NGL. After the determination of high consuming and inefficient elements, a relationship between economic costs and investment is also proposed and the components with the highest cost of exergy destruction have been identified.

The results of the exergy analysis show that the exergy efficiency of this process is around 53.83%, and its total exergy destruction rate is equal to 42617.5 kW. The results obtained from exergoeconomic analysis in the form of exergy destruction cost and exergoeconomic factor can be summarized as follows:

1. The most important elements in exergy destruction cost are heat exchangers due to the high value of fuel cost rate (as defined in exergoeconomic analysis) in these devices;
2. The exergoeconomic factor in compressors and turbo expander is higher than the other elements, and, hence, to reduce the total system cost, these elements costs must be minimized;
3. The exergoeconomic factor in heat exchangers and demethanizer tower compared to the other elements of the system is negligible, and, hence, to reduce the total system cost, the performance and efficiency of these elements must be maximized.

According to the above conclusions, the most important elements in the exergy destruction cost are heat exchangers. Therefore, the researchers should consider more effort on this element for improving this integrated process in the future studies. To decrease the costs, attention should be focused on decreasing the costs of compressor and turbo-expander by academic and industry experts.

## Nomenclature

| | |
|---|---|
| $f$ | : Exergoeconomic factor (%) |
| FC | : Fuel cost ($/s) |
| $i_{eff}$ | : Average annual discount rate (cost of money) |
| $j$ | : $j$th year of operation |
| OMC | : Operating and maintenance cost |
| PEC | : Purchase equipment cost ($) |
| $r$ | : Relative cost difference (%) |
| $r_{FC}$ | : Annual escalation rate for the fuel cost |
| ROI | : Return on investment |
| $r_{OM}$ | : Annual escalation rate for the operating and maintenance cost |
| TCR | : Total capital recovery |
| TRR | : Total revenue requirement |
| $\dot{W}$ | : Power (kW) |
| $Y$ | : Exergy destruction ratio |
| $\dot{Z}$ | : Total cost rate of component (capital investment & operating-maintenance cost) |
| **Greek Symbols** | |
| $\tau$ | : Annual operating hours (hr) |
| $\varepsilon$ | : Exergy efficiency |
| **Superscripts** | |
| CI | : Capital investment |
| OM | : Operating and maintenance |
| **Subscripts** | |
| $D$ | : Destruction |
| $F$ | : Fuel |
| $k$ | : $k$th component |
| $L$ | : Levelized |
| $P$ | : Production |
| **Abbreviations** | |
| AC | : Air cooler |

| | |
|---|---|
| C | : Compressor |
| D | : Flash drum |
| E | : Multi stream heat exchanger |
| Mix | : Mixer |
| V | : Expansion valve |
| TE | : Turbo expander |

## References


Bejan, A., Tsatsaronis, G., and Moran, M., Thermal Design and Optimization, New York, Wiley, 1996.

Elliot, D., Huang, S., Chen, J. J. (Roger), Lee, R. J., Yao, J., and Zhang, Y., (Irene) Benefits of Integrating NGL Extraction and LNG liquefaction Technology, AIChE Journal.,2005.

Finn, A. J., Developments in Natural Gas Liquefaction, Hydrocarbon Process, p. 47−59, 1999.

Garousi Farshi, L., Mahmoudi, S. M. S., and Rosen, M.A., Exergoeconomic Comparison of Double Effect and Combined Ejector-double Effect Absorption Refrigeration Systems, Applied Energy, Vol. 103, p.700–711, 2013.

Ghorbani, B., Salehi, G. R., Amidpour, M., and Hamedi, M. H., Exergy and Exergoeconomic Evaluation of Gas Separation Process, Journal of Natural Gas Science and Engineering, Vol. 9, p. 86-93, 2012.

Kanoglu, M., Exergy Analysis of Multistage Cascade Refrigeration Cycle Used for Natural Gas liquefaction, International Journal of Energy Research, Vol. 26, p. 763-774, 2002.

Lazzaretto, A. and Tsatsaronis, G., On the Quest for Objective Equations in Exergy Costing, Proceedings of the American Society of Mechanical Engineers (ASME) Advanced Energy Systems Division, American Society of Mechanical Engineers, New York. Vol. 37, p. 197-210, 1997.

Mafi, M., Mousavi Naeynian, S. M., and Amidpour, M., Exergy Analysis of Multistage Cascade Low Temperature Refrigeration Systems used in Olefin Plants, International Journal of Refrigeration, Vol. 32, p. 279–294, 2009.

Mehrpooya, M., Jarrahian, A., and Pishvaie, M. R., Simulation and Exergy-method Analysis of an Industrial Refrigeration Cycle used in NGL Recovery Units, International Journal of Energy Research, Vol. 30, p. 1336–1351, 2006.

Mehrpooya, M., Gharagheizi, F., and Vatani, A., Thermoeconomic Analysis of a Large Industrial Propane Refrigeration Cycle used in NGL Recovery Plant, International Journal of Energy Research, Vol. 33, p. 960-977, 2009.

Mehrpooya, M., Hossieni, M., and Vatani, A., Novel LNG-based Integrated Process Configuration Alternatives for Coproduction of LNG and NGL, Industrial & Engineering Chemistry Research, Vol. 53 p. 17705-17721, 2014.

Moreira, HL., Dias dos Santos, PH., Cunha Ribeiro, CM., Torres, EA., Ferreira Leite, AP., and Cabral dos Santos, CA., Exergoeconomic Analysis of a Double-effect Lithium Bromide-water Absorption Refrigeration System, In 18th International Congress of Mechanical Engineering, MG, Brazil, Ouro Preto, 2005.

Morosuk, T. and Tsatsaronis, G., A New Approach to the Exergy Analysis of Absorption Refrigeration Machines, Energy, Vol. 33, p. 890–90, 2008.

Morosuk, T., Tesch, S., Hiemann, A., Tsatsaronis, G., and Bin Omar, N., Evaluation of the PRICO Liquefaction Process using Exergy-based Methods, Journal of Natural Gas Science and Engineering, p. 1-9, 2015.

Remeljeja, C. W. and Hoadley, A. F. A., An Exergy Analysis of Small-scale Liquefied Natural Gas (LNG) Liquefaction Processes, Energy, Vol. 31, p. 2005-2019, 2006.

Shukri, T. LNG Technology Selection, Hydrocarbon Engineering, 2004.

Siddiqui, F. R., El-Shaarawi, M. A. I., and Said, S. A. M., Exergoeconomic Analysis of a Solar Driven Hybrid Storage Absorption Refrigeration Cycle, Energy Conversion and Management, Vol. 80, p. 165–172, 2014.

Technical Assessment Guide (TAGTM), TR-100281 Revision 6. Palo Alto, CA, Electric Power Research Institute, 1993.

Vatani, A., Mehrpooya, M., and Palizdar, A., Energy and Exergy Analyses of Five Conventional Liquefied Natural Gas Processes, International Journal of Energy Research, Vol. 38, p. 1843-1863, 2014.