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Evaluation of an Integrated Cryogenic Natural Gas Process with the Aid of Advanced Exergy and Exergoeconomic Analyses

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Abstract: In this study, an integrated structure of the air separation unit, natural gas liquids recovery equipped with nitrogen removal unit is developed. In this regard, advanced exergy and exergoeconomic analyses are used to examine the irreversibility, possible improvements and the cost of the inefficiencies of the process. The exergy analysis presents information on the origin of the irreversibility as well as the amount of irreversibility of each component. The results of advanced exergy analysis show that HX2, HX3, C1, C2, C3, AC1, AC3 equipment have the highest amount of the irreversibility due to endogenous exergy destruction, whereas the highest amount of the irreversibility in the rest of the equipment is because of exogenous exergy destruction. Furthermore, avoidable exergy destruction of equipment is more than the unavoidable exergy destruction in the C1, C2, and C3. This issue shows that with the improvement of the efficiency of the equipment, it is feasible to reduce the irreversibility of these systems. In addition, the results of advanced exergoeconomic analysis show that the priority to improve the performance of the system should be devoted to the HX2, HX3, C1, C3, AC1, AC3 equipment, respectively. The AC1 air cooler and the C3 compressor have the highest amounts of investment cost of avoidable endogenous exergy destruction, respectively. The heat exchanger HX3 and air cooler AC2 and AC3 have the lowest investment cost of avoidable endogenous exergy destruction.

keywords: Natural gas liquids, non-standard nitrogen separation, air separation unit, advanced exergy analysis, advanced exergoeconomic analysis

1. Introduction

Natural gas is considered as a clean source with a more suitable calorific value than oil (Aslani, Akbari et al. 2018). The importance and application of heavier hydrocarbons than methane in the conversion processes in addition to the hydrocarbon dew point setting to eliminate the operational problems caused by the liquefaction of heavy compounds in the transmission lines had led to a wide range of techniques and methods for the separation and recovery of hydrocarbon components of natural gas. On the other hand, the amount of nitrogen in the natural gas of Iran is between 0.5% and 11% (Niasar, Amidpour et al. 2017). With attention to the side effects of the presence of nitrogen with the gas on the thermal value of the fuel, the size of the transmission lines and the capacity of the gas pressure boost stations, it is usually used to the remove nitrogen from natural gas with concentrations of more than 4% at high flow rates. The design of an integrated structure in order to recycling of natural gas liquids and the removal of non-standard nitrogen from it is a necessity in the country. Simultaneous design of units and the

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integration of the process reduces the number of required equipment and energy consumption. Additionally, since the natural gas containing nitrogen cannot be sent into the gas supply lines because of its very low temperature from the nitrogen separator tower. Thus this cooling capacity is used to provide refrigeration of air separation units to produce pure oxygen (Qualls, Ransbarger et al. 2007). Many works related to Air Separation Unit (ASU) and Liquified Natural Gas (LNG) systems have been done which can be mentioned some of them. For instance, Smith et al. presented a comprehensive study of air separation technologies and their integration with energy conversion processes. They investigated different systems such as Non-cryogenic industrial gas processes, cryogenic industrial gas processes, hybrid air purification systems for large ASUs systems, etc (Smith and Klosek 2001). Dayviz et al. developed an integrated structure of natural gas liquids with nitrogen separation. Energy integration has been carried out between the distillation column of the nitrogen separator and the heat pump of the natural gas liquids recycling tower. This integrated structure is capable of separating 1% to 80% nitrogen from natural gas containing non-standard nitrogen (Wilkinson, Hudson et al. 2007). Mac neel et al. presented three different make-ups to remove nitrogen, that in these arrangements, nitrogen is removed from natural gas by a cryogenic distillation process including two separator towers (Mak and Graham 2013). These arrangements have a high ability to recycle 99.8% methane. Vatani et al. (Vatani, Mehrpooya et al. 2013) developed an integrated structure for the simultaneous production to recycle of natural gas liquids, liquefaction and natural gas production with domestic and industrial uses based on the refrigeration cycle C3MR with a specific energy consumption of 0.414 kWh / kg LNG and ethane recycling rate 93%. They used the method of connecting the HYSYS simulator software to the MATLAB language of programming, and the optimization environment of the genetic algorithm optimized the special energy consumption as a target function. This structure can be used to liquefaction of the large units in natural gas refineries. Mehrpooya et al. (Mehrpooya, Hossieni et al. 2014) developed three new integrated structure of simultaneous production of natural gas liquids and natural gas liquefaction based on the C3MR, DMR, and MFC refrigeration cycles. Total exergy yield of this system respectively, 55%, 56%, and 59%, with the rate the special energy consumption was 0.391, 0.375 and 0.336 kWh / kg LNG respectively. In this regard, the ASPEN HYSYS simulator using Peng-Robinson equation of state- employed to develop an integrated structure. Also, in order to simulate the recycle of natural gas liquids, the cooling expansion process of the cooled gas to recycle 90% of ethane from the natural gas was used. Hey et al. (He and Ju 2014) developed an integrated structure of simultaneous liquefaction and recycling of gas condensates, They used a genetic algorithm to optimize the developed integrated structure. Hey et al. [6] developed a simultaneously integrated structure of liquefaction and recycling of gas condensates, they used a genetic algorithm to optimize the developed integrated structure. Optimization results show that the energy consumption unit and the molar flow rate of the multi-component refrigerator respectively can be reduced by 9.64% and 11.68% compared to the initial state. They used exergy and economic analysis to evaluate the developed integrated structure. Ghorbani et al. (Ghorbani, Hamedi et al. 2016) developed a liquefaction integrated structure and recycling of natural gas liquids with a nitrogen separator unit. The simulation results show that the new integrated process has a 0.33 kWh / kg LNG specific energy consumption and a thermal efficiency of 62.82%. In addition, the sensitivity analysis shows that the integrated process structure is capable of removing nitrogen from natural gas at a concentration between 5% and 15%. Pillarella et al presents new technologies in the process, machinery, and the main cryogenic heat exchanger. They in this study investigated the new technologies related to the C3MR process, LNG, NGL/LPG in order to improve their efficiency in the future (Pillarella, Liu et al. 2007). Najibi et al. (Javanmardi, Nasrifar et al. 2005) investigated an Economic evaluation of natural gas transportation from the South-Pars area of Iran's. They investigated in this study the different technologies for transporting gas such as PNG, LNG, CNG and NGH (Najibi, Rezaei et al. 2009). Mehrpooya et al. (Mehrpooya and Sharifzadeh 2017) developed an integrated structure of the simultaneous production of pure oxygen and carbon dioxide. To power supply and refrigeration of this system, they used of combustion cycle with pure oxygen and LNG conversion to natural gas respectively. Also, they used exergy analysis and advanced exergoeconomic, to consider of cycle quality. Ghorbani et al. investigated a novel integrated process including recovery of natural gas liquids, natural gas liquefaction, and nitrogen rejection unit. They showed that process integration reduces the energy consumption and the number of the required equipment. Also, they proved that this system has a specific power of 0.359 (kWh/kg-LNG) and recover NGL more than 90% (Ghorbani, Hamedi et al. 2016).Jones et al. presented a study related to the optimal design and integration of an air separation unit (ASU) for an integrated gasification combined cycle. They investigated the power savings in different cycles about air integration between the ASU and the GT. They showed that if the nitrogen integration levels are less than 50–60%, it can have less power consumption in an LP-ASU with a PLOX cycle (Jones, Bhattacharyya et al. 2011). Mehrpooya et al. Introduced a novel air separation process based on cold energy recovery of LNG integrated with coal gasification (Mehrpooya, Esfilar et al. 2017). In this study presented a novel system containing coal gasification, transcritical CO_2 cycle, and CO_2 capture. They showed that it should be used to refrigeration supply, the recovery of the LNG cold energy. Besides, they showed that in this system, the amount of energy saving in the ASU and trans-critical power generation are 2301.6 kW and 14,217.6 kW. Lee et al. investigated the enhanced NGL recovery using refrigeration and reflux from LNG plants. They proved that with the use of this method, recoveries of propane and heavier components more than 95% are readily achievable (Lee, Yao et al. 2002). An investigation about the process to remove nitrogen and carbon dioxide from methane-containing streams has been done by Landrum et al. According to this study done in two stages, it will be removed the remarkable percent of nitrogen and carbon dioxide from the methane-containing stream (Landrum, Russell et al. 2008).

Ghorbani and Roshani employed advanced exergy and exergoeconomic analyses to evaluate an integrated structure of NGL recovery and liquefaction (Ghorbani and Roshani 2018). Bagheri et al. conducted exergy and advanced exergy analyses for an absorption refrigeration system (Bagheri, Shirmohammadi et al. 2019). Mehrpooya et al. investigated an advanced exergoeconomic analysis of the multi-stage mixed refrigerant systems (Mehrpooya and Ansarinasab 2015). In this study, they investigated three important parameters such as exergy efficiency, exergoeconomic factor, and total costs. They showed that the cost of investment and exergy destruction endogenous in the compressors is avoidable and it is unavoidable in heat exchangers and air coolers. On the other hand, they showed that in heat exchangers and air coolers, the investment cost is avoidable and in the compressors are unavoidable. Moharamian et al. employed advanced exergy and advanced exergoeconomic analyses of biomass and natural gas-fired combined cycles with hydrogen production (Moharamian, Soltani et al. 2018). Mehrpooya et al. (Mehrpooya and Ansarinasab 2015) investigated an advanced exergoeconomic evaluation of single mixed refrigerant natural gas liquefaction processes. They investigated advanced exergoeconomic analysis for two single mixed refrigerant processes. They concerning the obtained results showed that costs of investment and exergy destruction in most of the process components are endogenous. Also, they showed that the cost of exergy destruction in the compressors is avoidable and in other components are unavoidable. Ansarinasab et al. (Ansarinasab and Mehrpooya 2017) evaluated a novel process configuration for the coproduction of LNG and NGL. They presented three strategies for reducing exergy destruction costs.

The main aim of this study is to develop an integrated structure process of pure oxygen production units and the recycling of natural gas liquids along with the nitrogen separation unit. The exergy analysis is employed to find the origin of the irreversibility as well as the amount of irreversibility of each component. Next exergoeconomic is employed to evaluate the costs each process streams. Advanced exergy and exergoeconomic analyses are then employed to evaluate the integrated structure more precisely.

2. Process Description

In this research, the integrated structure is simulated by ASPEN HYSYS software and the equation of state (PRSV) is used for initial simulation, because this equation is a modified form of Peng-Robinson equation of state with different properties of this equation such as a wide range of temperature and pressure conditions in predicting the properties of light hydrocarbons and great accuracy for non-organic systems. Various scientific articles have used the Peng-Robinson equation of state to design processes in the integrated structures (Ghorbani, Mafi et al. 2013, Ghorbani, Mehrpooya et al. 2018). In these papers, C1 to C5 hydrocarbons and nitrogen were used as refrigerants to provide the required cooling of the process. In the developed integrated structure, the gas expansion-heating process of exceeding cooling is used for recycling the natural gas liquids. Related data of the natural gas fluid recycling unit has been extracted from the reference (Vatani, Mehrpooya et al. 2013). Table 1 illustrates the properties of feed and product streams and refrigeration systems for the C3MR process.

Fig. 1 shows the developed process flow diagram. The feed stream is cooled at 37 °C and a pressure 63 bar, respectively after passing of HX1, HX2 and HX3 exchangers to 41 °C. The output stream of this exchanger is two-phase and enters the separator D5. The separated vapor phase is divided into two parts. A portion of it, i.e. the G6 is liquated after passing of exchanger HX4, and expansion valve V8 is introduced into the highest tray of the NGL tower. The G7 stream after passing of a turbo-expander and reduction in pressure and temperature enters into the upper part of the NGL tower. The outlet liquid from the separator is divided into two parts. Table 2 represents thermodynamic data like temperature, pressure and flow rate of different streams for the C3MR process.

Table 1. Properties of feed, product streams and cooling system of process(Vatani, Mehrpooya et al. 2013)

Stream	CH_4	C_2H_6	C_3H_8	$C_4H_{10}^+$	C_2H_4	N_2	CO_2	O_2	Ar
Feed gas	0.80	0.05	0.03	0.02	0	0.07	0.001	0	0
NGL	0	0.46	0.31	0.20	0	0	0.01	0	0
Nitrogen	0.01	0	0	0	0	0.98	0	0	0
Nitrogen2	0	0	0	0	0	0.94	0	0.04	0.0120
Oxegen	0	0	0	0	0	0	0	0.99	0.0002
A1	0	0	0	0	0	0.78	0	0.21	0.01
G38	0.9880	0	0	0	0	0.0120	0	0	0
Side1	0	0.6449	0.2416	0.0894	0	0	0.0241	0	0
Side2	0	0.6518	0.1781	0.0928	0	0	0.0772	0	0
Side3	0.1256	0.4462	0.1732	0.0997	0	0.0002	0.1551	0	0

Table 2. Thermodynamic properties of streams for C3MR configuration

Stream no.	Temperature (°C)	Pressure (kPa)	Mass Flow (kg/h)	Stream no.	Temperature (°C)	Pressure (kPa)	Mass Flow (kg/h)
feedgas	37	6309	307425.31	222	-25.41	200	35269.78
G1	4	6309	307425.31	223	-25.41	200	496979.04
G2	-17	6309	307425.31	100	38	3800	1008011.19
G3	-41	6309	307425.31	101	4	3800	1008011.19
G4	-41	6309	66146.97	102	-17	3800	1008011.19
G5	-41	6309	241278.33	103	-28	3800	1008011.19
G6	-41	6309	96511.33	104	-28	3800	601124.27
G7	-41	6309	144767.002	105	-28	3800	406886.92
G8	-77	2600	144767.002	106	-129	3800	406886.92
G9	-41	6309	19844.09	107	-134.2	150	406886.92
G10	-41	6309	46302.88	108	-128	3800	601124.27
G11	-46.1	2550	46302.88	109	-169	3800	601124.27
G12	-92	6309	96511.33	110	-186.6	150	601124.27
G13	-105.2	2500	96511.33	111	-142.5	150	601124.27
G14	-62	6309	19844.09	112	-139	150	1008011.19
G15	-64.15	2500	19844.09	113	-77.45	150	1008011.19
G16	-100.8	2500	213732.53	113P	-67	150	1008011.19
G16P	-100.8	2500	213248.97	114	117	2200	1008011.19
G17	-115.2	1379	213248.97	115	38	2200	1008011.19
G18	-119	1379	213248.97	116	81.57	3800	1008011.19
G19	-163	1358	401907.29	side1R	35	2500	120200.87
G20	-163	1358	377792.85	side2R	0	2500	120904.03
G21	-163	1358	24114.43	side3R	-20	2500	121113.95
G22	-120	1358	24114.43	side1RR	35	2500	120244.68
G23	-65	1358	24114.43	side2RR	0	2500	120833.89
G24	-28	1358	24114.43	side3RR	-20	2500	121110.15
G25	1	1358	24114.43	side1	13.96	2500	120200.87
G26	-170	1358	377792.85	side2	6.239	2500	120904.03
G26P	-170	1358	374585.55	side3	-32.98	2500	121113.95
G27	-119.9	1400	250497.41	NGL	25.84	2500	93662.64

Stream no.	Temperature (°C)	Pressure (kPa)	Mass Flow (kg/h)	Stream no.	Temperature (°C)	Pressure (kPa)	Mass Flow (kg/h)
G28	-118	1400	250497.41	Oxegen	-8.222	410	68384.48
G28P	-118	1400	250762.70	A1	25	101.3	360000
G29	-118	1400	64842.88	A2	151.7	268	360000
G30	-118	1400	8059.97	A3	30	258	360000
G31	-75	1400	8059.97	A4	154.2	669	360000
G32	-118	1400	56782.91	A5	62	659	360000
G33	-132	1400	56782.91	A6	40.3	657	360000
G34	-132	1367	56782.91	A7	40.3	657	244800
G35	-118	1400	185919.82	A8	40.3	657	115200
G36	-108	1400	185919.82	A9	-164.1	647	244800
Nitrogen	20	1358	24114.43	A10	-173	647	115200
200	35	1430	1146522.003	A11	-178.6	517	147327.26
201	-14.19	300	1146522.003	A12	-171.9	649	212672.73
202	-14.19	300	386166.53	A13	-180.6	639	212672.73
203	-14.19	300	760355.46	A14	-185.6	507	147327.26
204	-14.19	300	228106.64	A15	-192.5	106	212672.73
205	-14.19	300	532248.82	A16	-195.3	106	147327.26
206	-14.19	300	228106.64	A17	-182.7	106	68384.48
207	-25.41	200	532248.82	A18	-182.6	235	68384.48
209	-25.41	200	337945.74	A19	-160	232	68384.48
210	-25.41	200	337945.74	A20	-133.1	412	68384.48
211	-25.41	200	159033.29	A21	-194.2	106	291615.51
212	-42.33	100	159033.29	A21P	-194.2	106	291614.28
213	-42.33	100	144502.506	A22	-175	103.5	291614.28
214	-21.48	100	144502.506	Nitrogen2	27	101	291614.28
215	-42.33	100	14530.78	G36P	-108	1400	184930.32
216	-23.34	100	159033.29	G37	-77.05	1390	184930.32
217	16.24	250	159033.29	G38	35.97	5900	184930.32
218	-16.72	200	532248.82	WT1	21.7	101.3	910800
219	23.98	500	532248.82	WT2	21.73	320	910800
220	-1.627	300	1146522.003	WT3	27.97	310	910800
221	71.76	1430	1146522.003	WT4	40.78	300	910800

One part of it, after passing of the exchanger HX4 and the expansion valve V7, enters to the middle of the tower and another part after passing of the expansion valve V6 and reducing temperature and pressure, enters to the high part of the tower. To remove the reboiler and condenser for better separation of ethane and provide heating and cooling of the tower, the three Side1, Side2, and Side3 streams are out from different trays of the tower respectively and after passing of heat exchanger, as recursive flows and with names Side1R, Side2R and Side3R re-enter to the tower. In this way, ethane and other heavier compounds, are out from the bottom of the tower as a liquid. In order to simulate the single-column nitrogen separator unit, it has been used from reference (He and Ju 2014). The stream of G16, which does not contain ethane and heavier compounds, after passing of expansion valve and exchanger HX4, enters the nitrogen removal tower. The stream of G18, at-119 °C and pressure about 13 bar, enter the tower NRU. The nitrogen is separated by steam from the top of the tower and divided into two streams of G20, G21. The streams G21, after passing of exchangers HX5, HX4, HX3, HX2, HX1 with 20 °C temperature and pressure about 13 bar, are out of the cycle as a produced nitrogen. The streams of G20, after passing of exchanger HX5 and liquefying, are sent to one of the top trays of the NRU tower as washer fluid. The separated fluid stream (G27) after passing through the exchanger HX4, enters the separator D6 and is divided into two sections. The separated vapor phase is divided into two parts from the top of the separator. A portion of it under a stream of G30 with the passing of exchangers HX5, HX4, is cooled and is sent to one of the top trays of the NRU tower. The stream G32, after passing of exchanger HX5 and expansion valve V10, enters to the tower NRU. The exiting liquid from the separator, called G35 which after passing of the exchangers HX4, HX6, is warmed to a temperature of 35 °C and with an increase in pressure up to 59 bar in the C7 compressor is injected into the pipeline as natural gas containing standard nitrogen. The G36 stream supplies a portion of cooling the air separation unit cycle to oxygen production. The water under the stream WT1, bypassing of the pump P100, increases pressure by 3.2 bar and bypassing of the exchangers HX9 and HX8, acts as a cooling fan. The stream of air A1, with an increase in pressure in the compressor C8 at 2.68 bar and under the temperature at 151.7 °C, enters the exchanger HX8 and then enters into the compressor C9. The stream A4 with a temperature of 154.2 °C and a pressure of 6.69 bar enters the exchangers HX9 and HX10, respectively and is cooled to 40.3 °C. 68% of the molar flow rate of A6 stream (stream A7), is cooled to -164.1 °C at HX6 and enters the down of tower T300. 32% of the molar flow rate of A6 stream (stream A8), is cooled up to -173 °C and injected to the top of tower T300. The A12 and A11 streams, respectively from the top and down of the tower T300 and with decrease pressure and temperature in exchanger and expansion valves, enter into the tower T400. The stream of A16, at -195.3 °C and pressure 1.06 bar, enters to the top of the tower and stream A15 under the temperature of -192.5 °C and a pressure of 1.06 bar, enters to a tray of 25 towers. The A21 stream containing 98% nitrogen, is exited from the top of the tower at -194 °C and is heated bypassing of the exchangers HX7 and HX6 and the gas containing pure almost nitrogen, is stored at a temperature of 27 °C. Outlet nitrogen from the top of the tower T400 provides a portion of the refrigeration of the air separation unit to produce oxygen. The A17 stream is containing 99.98% of pure oxygen is exited from the down of the tower at -183 °C and its pressure increases to 2.35 bar bypassing of pump P10. The stream of A18 bypassing of the exchanger HX6 and the compressor C6, under the stream of A20, with a temperature of -133 °C and a pressure of 4.12 bar respectively, enters to the HX10 exchanger and finally the stream containing pure oxygen, is exited from it at a temperature of -8.2 °C. In order to provide the required cooling of the developed integrated process, it has been used from the precooling propane cycle and the liquefaction with mixing refrigerant. The cycle of 200 as a pre-heating cycle, has the main task of providing required cooling to the intake feed and cooling source for the cooler cycles of the process. The outlet stream of the valve pressure is two-phase and enters separator D1. The separated liquid phase is divided into two parts. The stream of 204, enters the exchanger HX1 to provide the cooling required. The temperature and pressure of the stream 205, is reduced by passing of valve pressure V2, and the generated two-phase stream, enters into the separator D2. The separated liquid phase is divided into two parts. The stream of 209 enters the exchanger HX2 to cool required. The temperature and pressure of the stream 211 is reduced by passing of valve pressure V3, and the generated two-phase stream enters into the separator D3. The separated phase – liquid under the stream of 213, enters the exchanger HX3 to cooling supply. The separated vapor-liquid phase, under the stream 215, with the stream 214, passes of the compressor C1and increases their pressure. The outlet stream from the compressor C1, with produced vapor phase of the separator D2 and the stream 210, passes off the compressor C2 and increases their pressure. Besides the outlet stream from the compressor C2, with produced vapor phase of the separator D1 and the stream 206, passes off the compressor C3 and increases their pressure. The outlet stream of the compressor C3, bypassing the air cooler AC5, reaches a temperature of 36 degrees, thus completing the cycle. The final cooling cycle or liquefaction (cycle 100), has the ultimate task of liquefying and providing the required cooling of the removal nitrogen tower. The stream of 100, at 38 °C and 38 bar and after passing of the HX1, HX2, HX3 exchangers, is cooled to -28 ° C. Then the stream of 103, enters to the separator D4. The separated vapor-phase, bypassing of HX5, HX4 exchangers, is cooled to -169 °C. The output stream of the exchanger HX5 bypassing the valve pressure V9 is reduced its temperature and pressure and returning to provide cooling, enters the exchanger HX5. The separated liquid phase bypassing of the exchanger HX4 and the expansion valveV4 reduces its temperature and pressure. The outlet stream from the expansion valve (107), with the stream 111, bypassing of the exchanger HX4 and the heater E100, enters into the compressor C4 to increase the pressure. The outlet stream from the compressor C4 bypassing the air cooler AC2 reaches a temperature of 38 °C. After that, the pressure of the stream 115 bypassing of the compressor C5, increases by 38 bar. Finally, the stream of 116 bypassing of the air cooler AC3, reaches a temperature of 38 °C and this cycle is completed.

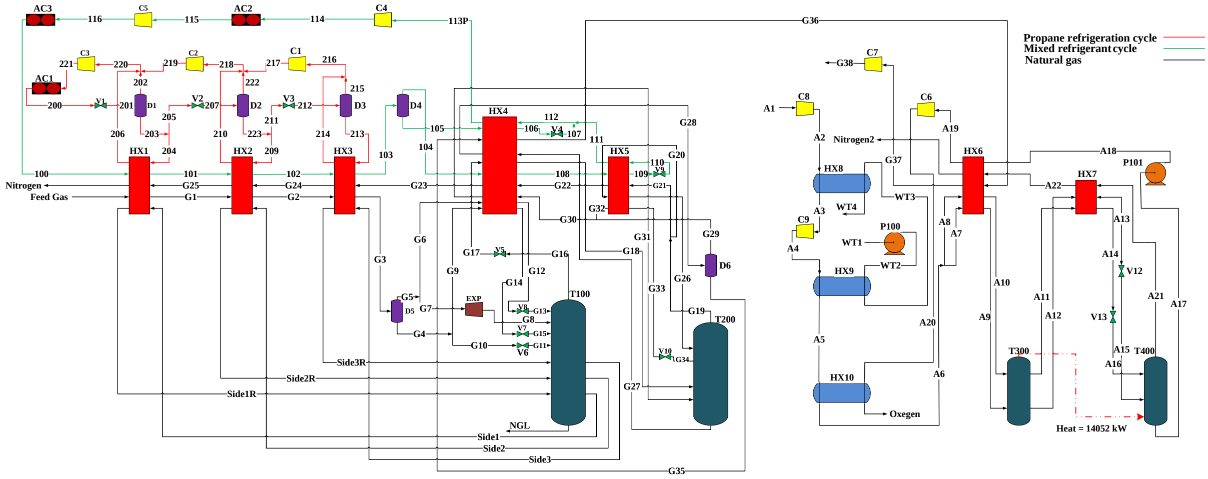

Figure 1. Schematic of the new integrated process

3. Advanced Exergy Analysis

In the analysis of exergy, although it can be determined the irreversibility of the components, this irreversibility cannot be subdivided from the source of their formation. Advanced exergy analysis is done based on the results of the exergy analysis. In this analysis, the irreversibility of equipment is divided into the two viewpoints, i.e. the origin of irreversibility and the ability to eliminate irreversibility. From the first point of view, the irreversibility of each device is divided into two categories: the endogenous irreversibility and the exogenous irreversibility. The endogenous irreversibility is part of the irreversibility relating to the inherent function of a device. Exogenous irreversibility is a part of the irreversibility which is the inductive effect of irreversibility to the other devices (Ghazizadeh, Ghorbani et al. 2018).
Hence, the exergy destruction of Kthcomponent is defined as follows:

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

There are two methods for calculating the endogenous exergy destruction; thermodynamic and engineering methods that in this paper engineering method is used. To do this, for each component of the process, the total exergy destruction diagram based on the destruction exergy, is plotted based on the following relationships as shown in Fig. 2 (Ansarinasab, Mehrpooya et al. 2017).

$$\dot{E}_{D,tot} = \dot{E}_{F,tot} - \dot{E}_{P,tot} \qquad (2)$$

$$\dot{E}_{D,tot} = \sum_k \dot{E}_{D,k} = \dot{E}_{D,k} + \dot{E}_{L,tot} \qquad (3)$$

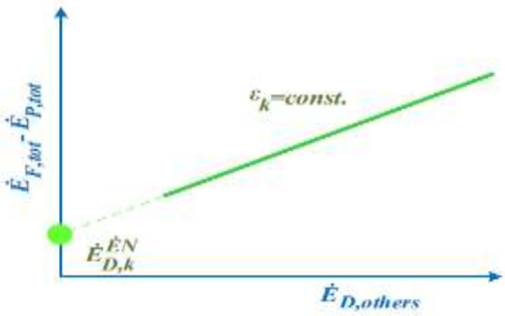

Figure 2. Schematic of the engineering method to calculate endogenous exergy destruction (Ansarinasab, Mehrpooya et al. 2017)

Fig. 2 shows the connection point of this diagram with the vertical axial of exogenous exergy destruction of the k component. The exogenous exergy destruction can be obtained by calculating the endogenous exergy destruction and using the following equation (Mehrpooya, Ansarinasab et al. 2018).

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

From the ability to eliminate irreversibility can be concluded that, the irreversibility of each device is divided into two avoidable unavoidable irreversibilities. Unavoidable irreversibility is a portion of the irreversibility that cannot be removed. The amount of exergy destruction can be expressed as follow (Fard and Pourfayaz 2019):

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

In this study, the assumptions of determining unavoidable irreversibility are presented in Table 3.

Table 3. Presumption of advanced exergoeconomic analysis

Component	Operating conditions
Compressor	90%
Multi-stream heat exchanger	ΔT_{min}= 0.5°C

Air cooler	ΔT_{min}= 5°C

The following relationships can obtain the unavoidable and avoidable exergy destruction values:

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

$$\dot{E}_{D,k}^{AV} = \dot{E}_{D,k} - \dot{E}_{D,k} \quad (7)$$

In the following, in order to better understand the role of each component, four categories of irreversibility can be created including unavoidable endogenous and exogenous as well as avoidable endogenous and exogenous exergy destruction (Mehdizadeh-Fard, Pourfayaz et al. 2018).

Endogenous and exogenous exergy destructioncan be defined as:

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

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

Also avoidable endogenous and exogenous exergy destruction can be defined as follows:

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

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

4. Exergoeconomicanalysis

Exergoeconomic analyses are combined with exergy and economic analyses. This analysis aims to obtain the exergy expense of each stream. First, the exergy of each process stream must be determined. Next, the cost of capital for each equipment should be calculated. Then the equation of cost balance for each item should be written. In general, this equation is written as follows (Shirmohammadi, Soltanieh et al. 2018):

$$\boldsymbol{c_{F,k}\dot{E}_{F,k} + \dot{Z} = c_{P,k}\dot{E}_{P,k}} \quad (12)$$

The auxiliary equations are required for components with more than one output stream. Thus, by writing the above relations for all process components as well as auxiliary relations, a linear equation of system which includes the unknown costs of the exergy unit is obtained for each stream. By solving this system, in addition, to calculating unknowns, the exergy cost of each stream can be calculated by the following equation:

$$\dot{C} = c\dot{E} \quad (13)$$

The exergy destruction cost can be calculated as follow:

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \quad (14)$$

4.1. Advanced Exergoeconomic Analysis

Similarly to the exergy destruction rate, the endogenous and exogenous parts of the investment cost and the cost of the exergy destruction rate are related to the internal operating conditions and the equipment interactions, respectively. Moreover, depending on whether the costs can be avoided, they can be split into avoidable and unavoidable parts. The endogenous and exogenous along with avoidable and unavoidable cost rates associated with the exergy destruction of the kth equipment are (Mehrpooya, Ansarinasab et al. 2018)**:**

$$\boldsymbol{\dot{C}_{D,k}^{EN} = c_{F,k}\dot{E}_{D,k}^{EN}} \quad (15)$$

$$\boldsymbol{\dot{C}_{D,k}^{EX} = c_{F,k}\dot{E}_{D,k}^{EX}} \quad (16)$$

$$\boldsymbol{\dot{C}_{D,k}^{UN} = c_{F,k}\dot{E}_{D,k}^{UN}} \quad (17)$$

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

The combination of endogenous/exogenous with avoidable/unavoidable exergy destruction cost can be lead to the following relationships (Mehrpooya, Ansarinasab et al. 2018):

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

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

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

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

Also, the investment cost of endogenous/ exogenous and avoidable/ unavoidable for each component can be calculated as the following relationships (Fard and Pourfayaz 2019):

$$\dot{Z}_{k}^{EN} = \dot{E}_{P,k}^{EN}\left(\frac{\dot{Z}}{\dot{E}_{P}}\right)_{k}^{real} \quad (23)$$

$$\dot{Z}_{k}^{EX} = \dot{Z}_{k} - \dot{Z}_{k}^{EN} \quad (24)$$

$$\dot{Z}_{k}^{UN} = \dot{E}_{P,k}\left(\frac{\dot{Z}}{\dot{E}_{P}}\right)_{k}^{UN} \quad (25)$$

$$\dot{Z}_{k}^{AV} = \dot{Z}_{k} - \dot{Z}_{k}^{UN} \quad (26)$$

All over again with the combination of irreversibilities, the following relations are obtained (Mehrpooya, Ansarinasab et al. 2018).

$$\dot{Z}_k^{UN,EN} = \dot{E}_{P,k}^{EN}\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{UN} \quad (27)$$

$$\dot{Z}_k^{UN,EX} = \dot{Z}_k^{UN} - \dot{Z}_k^{UN,EN} \quad (28)$$

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

$$\dot{Z}_k^{AV,EX} = \dot{Z}_k^{EX} - \dot{Z}_k^{UN,EX} \quad (30)$$

5. Results and Discussion

In Fig 3a to 3j, the combined curves of the heat exchangers are plotted. As shown in these Figs, heat exchangers in the integrated process structure have relatively optimal performance. About an integrated process structure, all exchangers have an optimal design which this subject is one of the reasons for the high efficiency of this process compared to other processes. Whatever the gas coolant curves and refrigerant heating get closer together, heat is transported more efficiently. Whatever the minimum temperature of the exchanger gets closer, a higher level of heat transfer is needed and will increase the overall volume of the exchanger as well as the complexity of its design. As a result, this factor cannot be reduced to any amount.

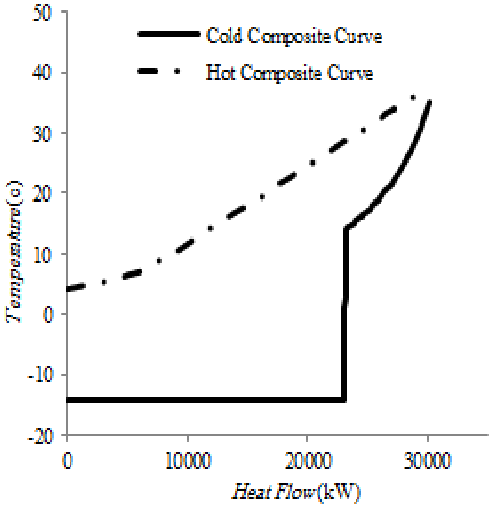

Figure 3 (a). Composite curves of HX1

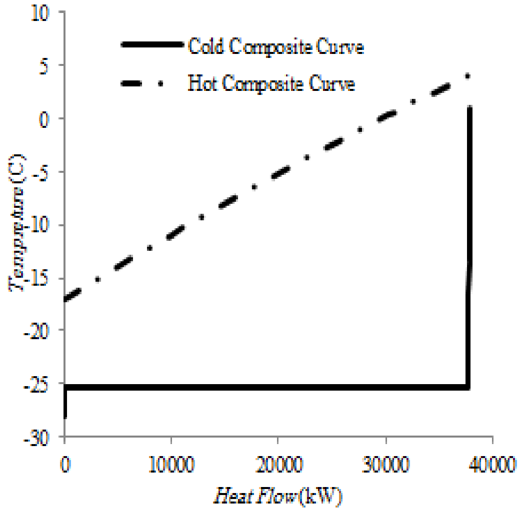

Figure 3 (b). Composite curves of HX2

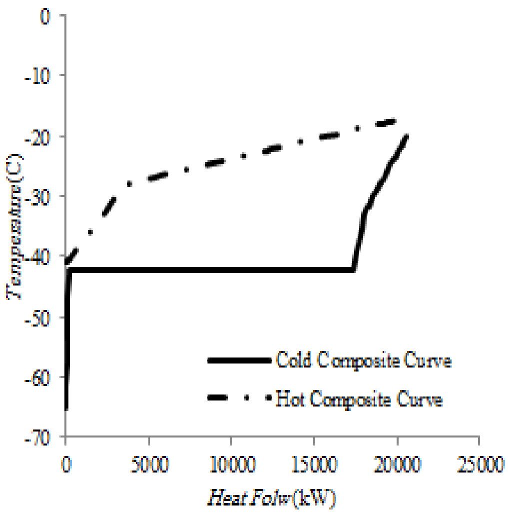

Figure 3 (c). Composite curves of HX3

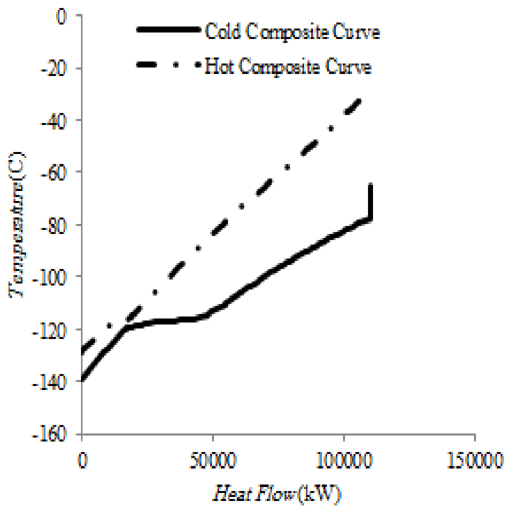

Figure 3 (d). Composite curves of HX4

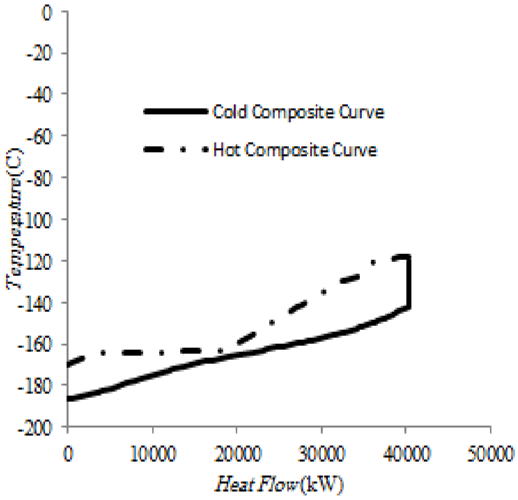

Figure 3 (e). Composite curves of HX5

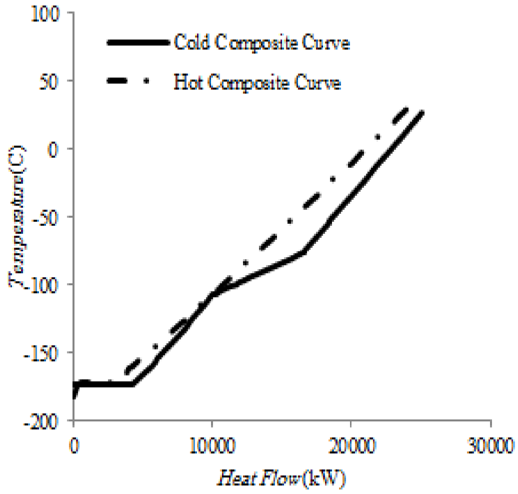

Figure 3 (f). Composite curves of HX6

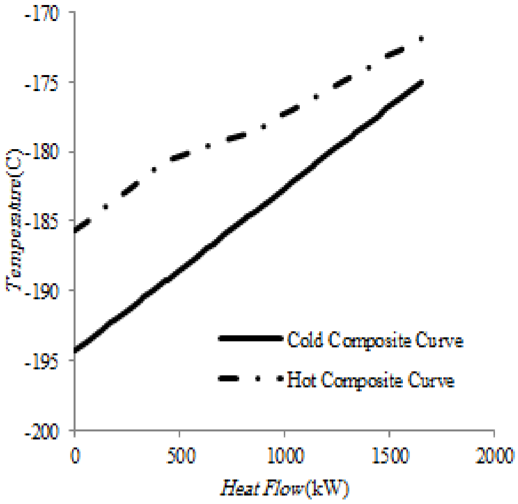

Figure 3 (g). Composite curves of HX7

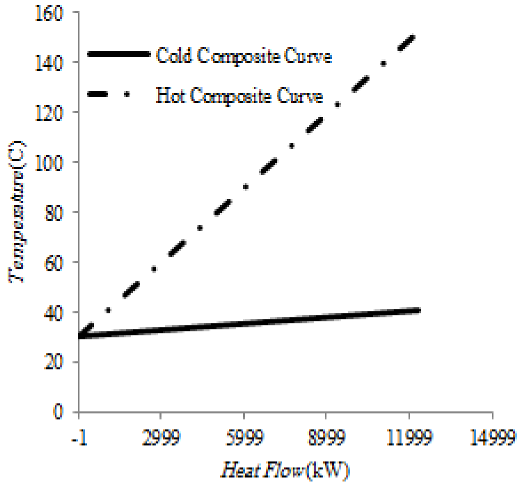

Figure 3 (h). Composite curve of HX8

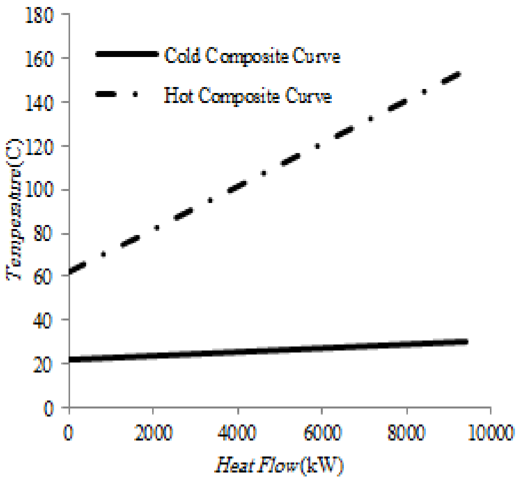

Figure 3 (i). Composite curves of HX9

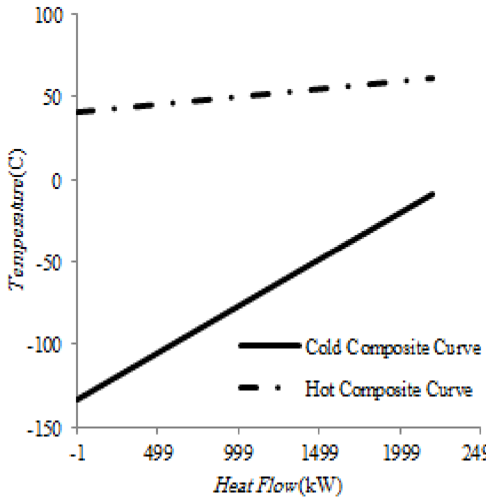

Figure 3 (j). Composite curves of HX10

Figure 3. The composite curves of the heat exchangers

In Table 4, the performance of the distillation tower of methane, nitrogen removal unit and towers of T400, T300 in the integrated structure are shown. The operational pressure of the distillation tower of the methane tower is 2500 kPa, and the operating pressure of the nitrogen removal unit is between 1358 to 1400 kPa. The inlet and outlet side of the removal of methane towers and the nitrogen removal unit, provide cooling at the top of the tower and heating at the bottom of the tower. In these two towers, condensers and reboilers removed by using integration with heat exchangers. In the methane tower, the three streams side1, side2 and side3 are removed from different trays and after heating in the heat exchangers, again enter a tray with similar process characteristics to that of side1R, side2R, and Side3R. If the pressure in the top and down of the tower gets closer, is increased the separation percentage of removing nitrogen from the natural gas. Whatever the pressure top and down the tower, NRU gets closer together, is increased the separation percentage of removing nitrogen from the natural gas.

Table 5 shows the performance of heat exchangers utilized in the integrated structure. The low-temperature difference between the hot and cold streams in the heat exchangers network and the continuation of this process reduces the consumption power of the cooling system due to the reduction of the loss of exergy in the exchanger network. By removing the reboiler and condenser in the separator towers, increases the number of streams added to the heat exchangers.

Hence, by removing the reboiler and condenser, the economic cost is reduced in the separator tower and on the other hand, we will be faced with greater complexity in the heat exchangers. The exchanger HX4 has the most thermal exchange with 110399.34 kW and the exchanger HX10, has the lowest thermal exchange with 2206.23 kW.

The performance of integrated structure air coolers, shown in Table 6. The air cooler AC1 with the highest airflow of 10727519.85 (kg/h), consumes the highest power of 192.85 kW.

Table 4. Specification of distillation towers performance in the new integrated process

Column	De-euthanizer Column	NRU Column	T300	T400
Tray No.	30	15	50	60
Side Stream Stages	Inlet 9-14-18-19-27 Outlet 18-26-29	Inlet 4-5	Inlet 50	Inlet 26
Feed Tray	1-9-14-18-19-27-30	1-4-5-15	50	1-26
Tray Efficiency	100	100	100	100
Top Pressure (kPa)	2500	1358	517	106
Bottom Pressure (kPa)	2500	1400	649	106

Table 5. Specification of the performance of heat exchangers in a new integrated process

Component	Log Mean Temperature Difference (LMTD)(℃)	Minimum Temperature Approach (℃)	Hot Pinch Temperature (℃)	Cold Pinch Temperature (℃)	Heat Duty (kW)	Number of Sides
HX1	19.07	3	38	35	30114.01	5
HX2	17.19	5.239	6.238	1	37868.64	5
HX3	11.98	1.89	-40.439	-42.33	20553.99	5
HX4	15.58	3.14	-116.779	-119.919	110399.34	10
HX5	11.04	2	-118	-120	40420.38	5
HX6	6.248	1.047	-106.953	-108	25122.06	5
HX7	5.654	3.131	-171.869	-175	1647.36	3
HX8	15.2	0.034	30	29.96	12330.18	2
HX9	72.68	40.27	62	21.73	9390.40	2
HX10	109.9	70.22	62	-8.221	2206.23	2

Table 6. Specification of the performance of air coolers in a new integrated process

Component	Minimum Temperature Approach (℃)	Air Outlet Temperature (℃)	Air Flow ($\frac{kg}{h}$)	Duty (kW)	Fan Power (kW)
AC1	7.771	65.86	10727519.85	123436.79	192.85
AC2	12.64	104.8	1872281.48	42104.46	35.71
AC3	13.12	68.33	1978923.45	24145.63	35.71

Fig.4 demonstrates the analysis of advanced exergy destruction of the studied process equipment. The exergy destruction of the process equipment is divided into four categories including avoidable, endogenous/ exogenous and unavoidable, endogenous/ exogenous and the amounts of each part are indicated in Fig.4. In the heat exchangers HX2, HX3 and the air coolers AC1, AC2, and AC3, the unavoidable exergy destruction is more than the avoidable part, while in the rest of the components, the avoidable exergy destruction is more than unavoidable. Also, except for AC2 in the rest of the components, endogenous exergy destruction is more than the exogenous part, which indicates that in these components, the most important source of irreversibility is the components themselves not the interaction between the components.

Fig.5 shows the analysis of advanced exergy destruction cost of the studied process equipment. The exergy destruction cost of the process equipment is divided into four categories including avoidable, endogenous/ exogenous and unavoidable, endogenous/ exogenous and the percentage effect of each part is indicated on the Fig.5 In the heat exchangers HX2, HX3 and the air coolers AC1, AC2, and AC3, the cost of the unavoidable exergy destruction are more than the avoidable, while in the rest of the components, the cost of the avoidable exergy destruction is more than unavoidable. Also, except for AC2 in the rest of the components, the cost of the endogenous exergy destruction is more than the exogenous. Meanwhile, in exchangers HX2 and HX3, compressor C2 and air coolers AC2, the amounts of cost of the avoidable exogenous exergy destruction are high, thus increasing the efficiency of equipment will have a major impact on reducing the irreversibility of the components. Table 7 demonstrates the cost rate balance equations and axillary equations of the studied process equipment.

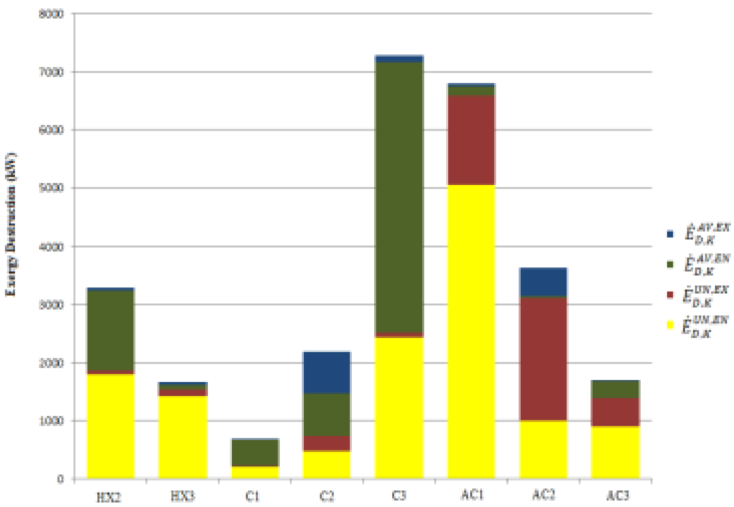

Figure 4. Exergy destruction of different parts of the process equipment

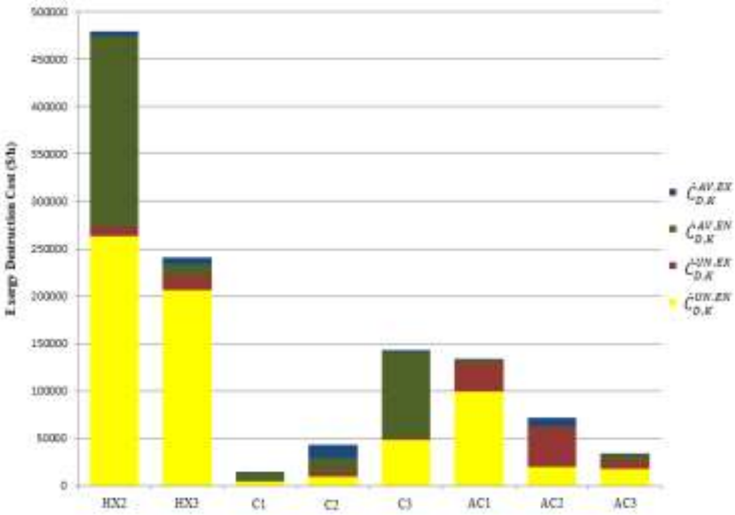

Figure 5. The cost of exergy destruction of different parts in the process equipment

Table 7. Main equations and auxiliary equations of the process components

Equipment	Main equation	Auxiliary equation
AC1	$\dot{C}_{221}+\dot{C}_{W}+\dot{Z}_{AC1}=\dot{C}_{200}$	-
AC2	$\dot{C}_{114}+\dot{C}_{W}+\dot{Z}_{AC2}=\dot{C}_{115}$	-
AC3	$\dot{C}_{116}+\dot{C}_{W}+\dot{Z}_{AC3}=\dot{C}_{100}$	-
C1	$\dot{C}_{216}+\dot{C}_{W}+\dot{Z}_{C1}=\dot{C}_{217}$	-
C2	$\dot{C}_{218}+\dot{C}_{W}+\dot{Z}_{C2}=\dot{C}_{219}$	-
C3	$\dot{C}_{220}+\dot{C}_{W}+\dot{Z}_{C3}=\dot{C}_{221}$	-
C4	$\dot{C}_{113P}+\dot{C}_{W}+\dot{Z}_{C4}=\dot{C}_{114}$	-
C5	$\dot{C}_{115}+\dot{C}_{W}+\dot{Z}_{C5}=\dot{C}_{116}$	-
C6	$\dot{C}_{A19}+\dot{C}_{W}+\dot{Z}_{C6}=\dot{C}_{A20}$	-
C7	$\dot{C}_{G37}+\dot{C}_{W}+\dot{Z}_{C7}=\dot{C}_{G38}$	-
C8	$\dot{C}_{A1}+\dot{C}_{W}+\dot{Z}_{C8}=\dot{C}_{A2}$	-
C9	$\dot{C}_{A3}+\dot{C}_{W}+\dot{Z}_{C9}=\dot{C}_{A4}$	-
D1	$\dot{C}_{201}+\dot{Z}_{D1}=\dot{C}_{202}+\dot{C}_{203}$	$\frac{\dot{C}_{202}}{\dot{E}_{202}}=\frac{\dot{C}_{203}}{\dot{E}_{203}}$
D2	$\dot{C}_{207}+\dot{Z}_{D2}=\dot{C}_{222}+\dot{C}_{223}$	$\frac{\dot{C}_{222}}{\dot{E}_{222}}=\frac{\dot{C}_{223}}{\dot{E}_{223}}$
D3	$\dot{C}_{212}+\dot{Z}_{D3}=\dot{C}_{213}+\dot{C}_{215}$	$\frac{\dot{C}_{213}}{\dot{E}_{213}}=\frac{\dot{C}_{215}}{\dot{E}_{215}}$
D4	$\dot{C}_{103}+\dot{Z}_{D4}=\dot{C}_{104}+\dot{C}_{105}$	$\frac{\dot{C}_{104}}{\dot{E}_{104}}=\frac{\dot{C}_{105}}{\dot{E}_{105}}$
D5	$\dot{C}_{G3}+\dot{Z}_{D5}=\dot{C}_{G4}+\dot{C}_{G5}$	$\frac{\dot{C}_{G4}}{\dot{E}_{G4}}=\frac{\dot{C}_{G5}}{\dot{E}_{G5}}$
D6	$\dot{C}_{G28P}+\dot{Z}_{D6}=\dot{C}_{G29}+\dot{C}_{G35}$	$\frac{\dot{C}_{G29}}{\dot{E}_{G29}}=\frac{\dot{C}_{G35}}{\dot{E}_{G35}}$
EXP	$\dot{C}_{G7}+\dot{Z}_{EXP}=\dot{C}_{G8}+\dot{C}_{W}$	
HX1	$\dot{C}_{feedgas}+\dot{C}_{100}+\dot{C}_{204}+\dot{C}_{side1}+\dot{C}_{G25}+\dot{Z}_{HX1}=\dot{C}_{G1}+\dot{C}_{101}+\dot{C}_{206}+\dot{C}_{side1R}+\dot{C}_{Nitrogen}$	$\frac{\dot{C}_{G25}}{\dot{E}_{G25}}=\frac{\dot{C}_{Nitrogen}}{\dot{E}_{Nitrogen}},\frac{\dot{C}_{side1}}{\dot{E}_{side1}}=\frac{\dot{C}_{side1R}}{\dot{E}_{side1R}},\frac{\dot{C}_{204}}{\dot{E}_{204}}=\frac{\dot{C}_{206}}{\dot{E}_{206}},$ $\frac{\dot{C}_{101}-\dot{C}_{100}}{\dot{E}_{101}-\dot{E}_{100}}=\frac{\dot{C}_{G1}-\dot{C}_{feedgas}}{\dot{E}_{G1}-\dot{E}_{feedgas}}$
HX10	$\dot{C}_{A5}+\dot{C}_{A20}+\dot{Z}_{HX10}=\dot{C}_{A6}+\dot{C}_{Oxegen}$	$\frac{\dot{C}_{A6}-\dot{C}_{A5}}{\dot{E}_{A6}-\dot{E}_{A5}}=\frac{\dot{C}_{Oxegen}-\dot{C}_{A20}}{\dot{E}_{Oxegen}-\dot{E}_{A20}}$
HX2	$\dot{C}_{G1}+\dot{C}_{101}+\dot{C}_{209}+\dot{C}_{side2}+\dot{C}_{G24}+\dot{Z}_{HX2}=\dot{C}_{G2}+\dot{C}_{102}+\dot{C}_{210}+\dot{C}_{side2R}+\dot{C}_{G25}$	$\frac{\dot{C}_{G24}}{\dot{E}_{G24}}=\frac{\dot{C}_{G25}}{\dot{E}_{G25}},\frac{\dot{C}_{side2}}{\dot{E}_{side2}}=\frac{\dot{C}_{side2R}}{\dot{E}_{side2R}},\frac{\dot{C}_{209}}{\dot{E}_{209}}=\frac{\dot{C}_{210}}{\dot{E}_{210}},$ $\frac{\dot{C}_{102}-\dot{C}_{101}}{\dot{E}_{102}-\dot{E}_{101}}=\frac{\dot{C}_{G2}-\dot{C}_{G1}}{\dot{E}_{G2}-\dot{E}_{G1}}$
HX3	$\dot{C}_{G2}+\dot{C}_{102}+\dot{C}_{213}+\dot{C}_{side3}+\dot{C}_{G23}+\dot{Z}_{HX3}=\dot{C}_{G3}+\dot{C}_{103}+\dot{C}_{214}+\dot{C}_{side3R}+\dot{C}_{G24}$	$\frac{\dot{C}_{G23}}{\dot{E}_{G23}}=\frac{\dot{C}_{G24}}{\dot{E}_{G24}},\frac{\dot{C}_{side3}}{\dot{E}_{side3}}=\frac{\dot{C}_{side3R}}{\dot{E}_{side3R}},\frac{\dot{C}_{213}}{\dot{E}_{213}}=\frac{\dot{C}_{214}}{\dot{E}_{214}},$ $\frac{\dot{C}_{103}-\dot{C}_{102}}{\dot{E}_{103}-\dot{E}_{102}}=\frac{\dot{C}_{G3}-\dot{C}_{G2}}{\dot{E}_{G3}-\dot{E}_{G2}}$
HX4	$\dot{C}_{104}+\dot{C}_{105}+\dot{C}_{112}+\dot{C}_{G6}+\dot{C}_{G9}+\dot{C}_{G17}+\dot{C}_{G35}+\dot{C}_{G27}+\dot{C}_{G30}+\dot{C}_{G22}+\dot{Z}_{HX4}=\dot{C}_{108}+\dot{C}_{106}+\dot{C}_{113}+\dot{C}_{G12}+\dot{C}_{G14}+\dot{C}_{G18}+\dot{C}_{G36}+\dot{C}_{G28}+\dot{C}_{G31}+\dot{C}_{G23}$	$\frac{\dot{C}_{G22}}{\dot{E}_{G22}}=\frac{\dot{C}_{G23}}{\dot{E}_{G23}},\frac{\dot{C}_{G30}}{\dot{E}_{G30}}=\frac{\dot{C}_{G31}}{\dot{E}_{G31}},\frac{\dot{C}_{G27}}{\dot{E}_{G27}}=\frac{\dot{C}_{G28}}{\dot{E}_{G28}},\frac{\dot{C}_{112}}{\dot{E}_{112}}=\frac{\dot{C}_{113}}{\dot{E}_{113}}$ $\frac{\dot{C}_{G36}-\dot{C}_{G35}}{\dot{E}_{G36}-\dot{E}_{G35}}=\frac{\dot{C}_{G18}-\dot{C}_{G17}}{\dot{E}_{G18}-\dot{E}_{G17}}=\frac{\dot{C}_{G14}-\dot{C}_{G9}}{\dot{E}_{G14}-\dot{E}_{G9}}=\frac{\dot{C}_{G12}-\dot{C}_{G6}}{\dot{E}_{G12}-\dot{E}_{G6}}=\frac{\dot{C}_{106}-\dot{C}_{105}}{\dot{E}_{106}-\dot{E}_{105}}=\frac{\dot{C}_{108}-\dot{C}_{104}}{\dot{E}_{108}-\dot{E}_{104}}$
HX5	$\dot{C}_{108}+\dot{C}_{110}+\dot{C}_{G32}+\dot{C}_{G20}+\dot{C}_{G21}+\dot{Z}_{HX5}=\dot{C}_{109}+\dot{C}_{111}+\dot{C}_{G33}+\dot{C}_{G26}+\dot{C}_{G22}$	$\frac{\dot{C}_{G22}}{\dot{E}_{G22}}=\frac{\dot{C}_{G21}}{\dot{E}_{G21}},\frac{\dot{C}_{111}}{\dot{E}_{111}}=\frac{\dot{C}_{110}}{\dot{E}_{110}},$ $\frac{\dot{C}_{G26}-\dot{C}_{G20}}{E_{G26}-\dot{E}_{G20}}=\frac{\dot{C}_{G33}-\dot{C}_{G32}}{\dot{E}_{G33}-\dot{E}_{G32}}=\frac{\dot{C}_{109}-\dot{C}_{108}}{\dot{E}_{109}-\dot{E}_{108}}$
HX6	$\dot{C}_{G36P}+\dot{C}_{A22}+\dot{C}_{A18}+\dot{C}_{A7}+\dot{C}_{A8}+\dot{Z}_{HX6}=\dot{C}_{G37}+\dot{C}_{Nitrogen2}+\dot{C}_{A19}+\dot{C}_{A9}+\dot{C}_{A10}$	$\frac{\dot{C}_{A18}}{\dot{E}_{A18}}=\frac{\dot{C}_{A19}}{\dot{E}_{A19}},\frac{\dot{C}_{A22}}{\dot{E}_{A22}}=\frac{\dot{C}_{Nitrogen2}}{\dot{E}_{Nitrogen2}},\frac{\dot{C}_{G36P}}{\dot{E}_{G36P}}=\frac{\dot{C}_{G37}}{\dot{E}_{G37}},$ $\frac{\dot{C}_{A10}-\dot{C}_{A8}}{\dot{E}_{A10}-\dot{E}_{A8}}=\frac{\dot{C}_{A9}-\dot{C}_{A7}}{\dot{E}_{A9}-\dot{E}_{A7}}$

Equipment	Main equation	Auxiliary equation
HX7	$\dot{C}_{A11}+\dot{C}_{A12}+\dot{C}_{A21P}+\dot{Z}_{HX7}=\dot{C}_{A14}+\dot{C}_{A13}+\dot{C}_{A22}$	$\frac{\dot{C}_{A21P}}{\dot{E}_{A21P}}=\frac{\dot{C}_{A22}}{\dot{E}_{A22}},\frac{\dot{C}_{A13}-\dot{C}_{A12}}{\dot{E}_{A13}-\dot{E}_{A12}}=\frac{\dot{C}_{A14}-\dot{C}_{A11}}{\dot{E}_{A14}-\dot{E}_{A11}}$
HX8	$\dot{C}_{A2}+\dot{C}_{WT3}+\dot{Z}_{HX8}=\dot{C}_{A3}+\dot{C}_{WT4}$	$\frac{\dot{C}_{A3}-\dot{C}_{A2}}{\dot{E}_{A3}-\dot{E}_{A2}}=\frac{\dot{C}_{WT4}-\dot{C}_{WT3}}{\dot{E}_{WT4}-\dot{E}_{WT3}}$
HX9	$\dot{C}_{A4}+\dot{C}_{WT2}+\dot{Z}_{HX9}=\dot{C}_{A5}+\dot{C}_{WT3}$	$\frac{\dot{C}_{A5}-\dot{C}_{A4}}{\dot{E}_{A5}-\dot{E}_{A4}}=\frac{\dot{C}_{WT3}-\dot{C}_{WT2}}{\dot{E}_{WT3}-\dot{E}_{WT2}}$
MIX1	$\dot{C}_{107}+\dot{C}_{111}=\dot{C}_{112}$	-
MIX2	$\dot{C}_{214}+\dot{C}_{215}=\dot{C}_{216}$	-
MIX3	$\dot{C}_{210}+\dot{C}_{222}+\dot{C}_{217}=\dot{C}_{218}$	-
MIX4	$\dot{C}_{202}+\dot{C}_{206}+\dot{C}_{219}=\dot{C}_{220}$	-
P100	$\dot{C}_{WT1}+\dot{C}_{W}+\dot{Z}_{P100}=\dot{C}_{WT2}$	-
P101	$\dot{C}_{A17}+\dot{C}_{W}+\dot{Z}_{P101}=\dot{C}_{A18}$	-
TEE	$\dot{C}_{A6}=\dot{C}_{A8}+\dot{C}_{A7}$	$\frac{\dot{C}_{A8}}{\dot{E}_{A8}}=\frac{\dot{C}_{A7}}{\dot{E}_{A7}}$
T100	$\dot{C}_{G8}+\dot{C}_{G15}+\dot{C}_{G13}+\dot{C}_{side2RR}+\dot{C}_{side3RR}+\dot{C}_{side1RR}+\dot{C}_{G11}+\dot{Z}_{T100}=\dot{C}_{NGL}+\dot{C}_{side1}+\dot{C}_{side3}+\dot{C}_{side2}+\dot{C}_{G16}$	$\frac{\dot{C}_{G16}}{\dot{E}_{G16}}=\frac{\dot{C}_{NGL}}{\dot{E}_{NGL}},\frac{\dot{C}_{side1}}{\dot{E}_{side1}}=\frac{\dot{C}_{204}}{\dot{E}_{204}},\frac{\dot{C}_{side3}}{\dot{E}_{side3}}=\frac{\dot{C}_{213}}{\dot{E}_{213}},$ $\frac{\dot{C}_{side2}}{\dot{E}_{side2}}=\frac{\dot{C}_{209}}{\dot{E}_{209}}$
T200	$\dot{C}_{G26P}+\dot{C}_{G18}+\dot{C}_{G31}+\dot{C}_{G34}+\dot{Z}_{T200}=\dot{C}_{G19}+\dot{C}_{G27}$	$\frac{\dot{C}_{G27}}{\dot{E}_{G27}}=\frac{\dot{C}_{G19}}{\dot{E}_{G19}}$
T300	$\dot{C}_{A10}+\dot{C}_{A9}+\dot{Z}_{T300}=\dot{C}_{A11}+\dot{C}_{A12}+\dot{C}_{W}$	$\frac{\dot{C}_{A11}}{\dot{E}_{A11}}=\frac{\dot{C}_{A12}}{\dot{E}_{A12}}$
T400	$\dot{C}_{A15}+\dot{C}_{A16}+\dot{C}_{W}+\dot{Z}_{T400}=\dot{C}_{A17}+\dot{C}_{A21}$	$\frac{\dot{C}_{A17}}{\dot{E}_{A17}}=\frac{\dot{C}_{A21}}{\dot{E}_{A21}}$
TEE1	$\dot{C}_{203}=\dot{C}_{204}+\dot{C}_{205}$	$\frac{\dot{C}_{205}}{\dot{E}_{205}}=\frac{\dot{C}_{204}}{\dot{E}_{204}}$
TEE100	$\dot{C}_{G5}=\dot{C}_{G6}+\dot{C}_{G7}$	$\frac{\dot{C}_{G6}}{\dot{E}_{G6}}=\frac{\dot{C}_{G7}}{\dot{E}_{G7}}$
TEE101	$\dot{C}_{G4}=\dot{C}_{G9}+\dot{C}_{G10}$	$\frac{\dot{C}_{G9}}{\dot{E}_{G9}}=\frac{\dot{C}_{G10}}{\dot{E}_{G10}}$
TEE104	$\dot{C}_{G19}=\dot{C}_{G20}+\dot{C}_{G21}$	$\frac{\dot{C}_{G21}}{\dot{E}_{G21}}=\frac{\dot{C}_{G20}}{\dot{E}_{G20}}$
TEE105	$\dot{C}_{G29}=\dot{C}_{G30}+\dot{C}_{G32}$	$\frac{\dot{C}_{G30}}{\dot{E}_{G30}}=\frac{\dot{C}_{G32}}{\dot{E}_{G32}}$
TEE2	$\dot{C}_{223}=\dot{C}_{209}+\dot{C}_{211}$	$\frac{\dot{C}_{209}}{\dot{E}_{209}}=\frac{\dot{C}_{211}}{\dot{E}_{211}}$
V1	$\dot{C}_{200}=\dot{C}_{201}$	-
V10	$\dot{C}_{G33}=\dot{C}_{G34}$	-
V12	$\dot{C}_{A13}=\dot{C}_{A15}$	-
V13	$\dot{C}_{A14}=\dot{C}_{A16}$	-
V2	$\dot{C}_{205}=\dot{C}_{207}$	-
V3	$\dot{C}_{211}=\dot{C}_{212}$	-
V4	$\dot{C}_{106}=\dot{C}_{107}$	-
V5	$\dot{C}_{G16P}=\dot{C}_{G17}$	-
V6	$\dot{C}_{G10}=\dot{C}_{G11}$	-
V7	$\dot{C}_{G14}=\dot{C}_{G15}$	-
V8	$\dot{C}_{G12}=\dot{C}_{G13}$	-
V9	$\dot{C}_{109}=\dot{C}_{110}$	-
E100	$\dot{C}_{113}+\dot{C}_{W}+\dot{Z}_{E100}=\dot{C}_{113P}$	-

In Fig.6, the analysis of the advanced investment cost of process equipment has been done. The investment cost of the exergy destruction of the process equipment is divided into four categories including avoidable, endogenous/ exogenous and unavoidable, endogenous/ exogenous and is indicated in Fig. 6, the percentage effect of each part. Except for the air cooler AC2, in which the investment cost of the endogenous part is more than the endogenous part, the investment cost of the endogenous part is more than the exogenous part for the rest of the equipment. Also, in all parts, the investment cost of the unavoidable part is more than the avoidable part. Meanwhile, about that the advanced investment cost of the avoidable endogenous for the exchanger HX2, the compressor C3, and the air cooler AC1 is high, hence, there is a great potential for improving their performance through increased efficiency, which with this can reduce the amount of investment cost to them.

In the advanced exergoeconomic analysis, parameters can be defined to compare the performance of the components. These parameters based on the cost of exergy destruction and investment cost of avoidable exogenous, are shown in Table 8.

The air coolers AC2, AC3, and AC1, have the highest exergy efficiency with 99.9%, 99.6%, and 99.5% respectively. Also, the exchanger HX2 and compressors C1 and C3, respectively with 76.1%, 81.5%, and 84.7% and have the least amount of modified exergy efficiency. The modified exert economic factor is an important parameter that gives us valuable information related to processing components modification. When the value of this coefficient for the components is high, it shows that should be reduced the investment cost to reduce the cost of the process. Also, the components with the low modified exergoeconomic coefficient should be increased their efficiency. As can be seen, air coolers and compressors, have the highest amount of modified exergeconomic factors, and it is necessary to be considered their investment costs to improve the process.

Table 9 shows strategies that can be used for reducing the avoidable cost of exergy destruction of the process components. In this Table, three strategies are introduced which can be used for improvement. Selection must be made based on the results of the advanced exergoeconomic parameters.

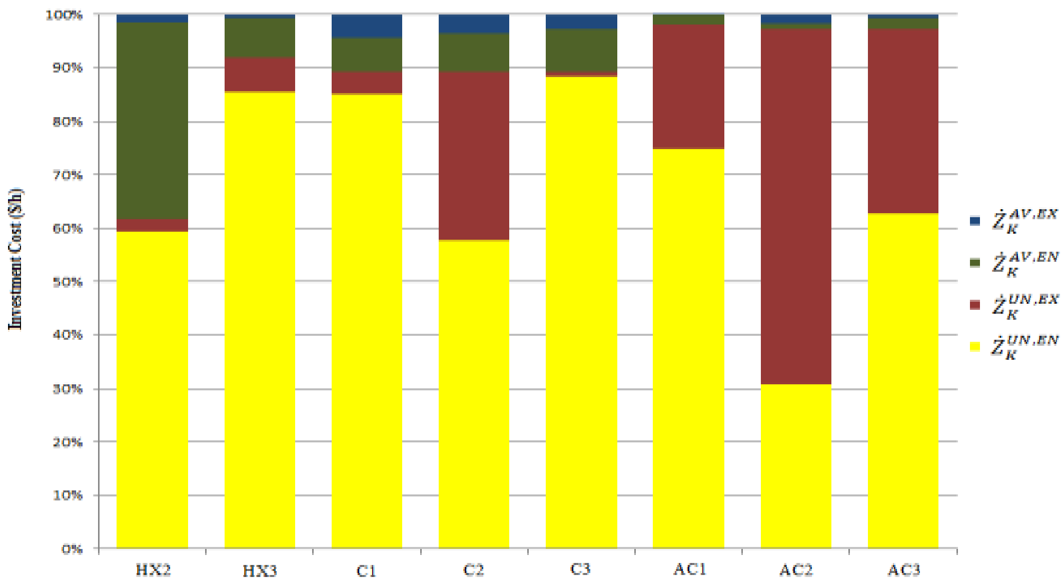

Figure 6. Various parts of advanced investment cost in process equipment

Table 8. Comparison of process equipment performance

Component	$\varepsilon_{modified}$	$f_k^{AV,EN}$	$\dot{C}_{tot}^{AV,EN}$
HX2	0.76124151	0.0000053	200670.0631
HX3	0.978911663	0.0000129	12823.80809
C1	0.815401844	0.0001524	8562.111829
C2	0.897055327	0.00021387	14540.93051
C3	0.847498079	0.0000875	91391.15181
AC1	0.995703444	0.011501006	3327.965351
AC2	0.999557391	0.000570617	689.2128763
AC3	0.996622317	0.000122269	5968.790599

Table 9. Strategies for reducing the avoidable cost of exergy destruction

Component	Cost of exergy destruction categories ($/h)				The part should be focused	Possible strategies to reduce the cost of exergy destruction		
	$\dot{C}_D$	$\dot{C}_{D,K}^{AV}$	$\dot{C}_{D,K}^{AV,EN}$	$\dot{C}_{D,K}^{AV,EX}$		Strategy A[a]	Strategy B[b]	Strategy C[c]
HX2	479796.5	206426.7	200668.98	5757.7666	EN	*		
HX3	241166	19853.68	12823.642	7030.0355	EN/EX	*	*	
C1	13393.01	8923.772	8560.807	362.96548	EN	*		
C2	43229.03	28724.42	14537.821	14186.601	EN/EX	*	*	*
C3	143301.5	93621.89	91383.15	2238.7375	EN	*		
AC1	134052.4	4146.733	3289.6904	857.04262	EN	*		
AC2	71614.76	10368.32	688.8196	9679.4956	EX		*	*
AC3	33493.39	6255.397	5968.0608	287.33615	EN	*		

[a] Strategy A: Improving the efficiency of the kth 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.

According to the research, it can be the alternative for the production of natural gas liquids due to the increasing use of the product downstream natural gas industry, and the cost-effectiveness of the product, simulations and analysis advanced exergy and advanced exergoeconomics on them.

➢ Provide better alignment equipment to optimize the process:

The process can be optimized by changing the alignment of process equipment to achieve high performance. For example, a Joule-Thomson recover work lost in the expansion valve with the expansion, we can reduce our consumption of compressors. Since compressors are energy-consuming equipment, thus recovering lost work both increases process efficiency and reduces energy consumption.

➢ The effect of changes in conditions of natural gas feedstock to the operating system:

The change in temperature, pressure, and composition of natural gas feed components can affect the composition of the mixed refrigerants, the energy consumption of the compressors, and the size of the process equipment. Therefore, a combination of mixed refrigerant liquefaction and sub-cooling that would feed natural gas makes the slightest problem with is very important. Usually, bypassing seasons, the feed conditions are subject to changes. Therefore, optimizing the combination of refrigerants to maintain high process efficiency and lower energy consumption during the change over period attracts much attention.

➢ Dynamic simulation of cooling cycles:

Dynamic simulation of the process unit is very important in monitoring and observing unit changes over time, and this helps in dynamically optimizing processes to understand the process of changes in the cooling system.

6. Conclusion

Advanced exergy and exergoeconomic analyses have been conducted in an integrated cryogenic process including natural gas liquids (NGL), nitrogen removal unit (NRU) and air separation unit (ASU). The results of the processes analysis are as follows:

Based on the results, the cost of endogenous exergy destruction related to HX2, HX3, C1, C2, C3, AC1, and AC3 equipment is more than the other equipment. Moreover, the compressor C3 has the highest amount of avoidable endogenous exergy destruction that increasing the efficiency of the equipment will have a significant impact on reducing this amount. The results of the investment cost of avoidable endogenous exergy destruction show that the heat exchanger HX2, the compressor C2, and the air cooler AC1 have a high ability for modification of their performance by improving their efficiency. It should be noted that the AC1 air cooler and the C3 compressor have a higher amount of investment cost of avoidable endogenous exergy destruction among the equipment, respectively. Furthermore, the heat exchanger HX3 and air cooler AC2 and AC3 have had the lowest investment cost of avoidable endogenous exergy destruction. Finally, based on the presented results of the total cost of avoidable endogenous exergy destruction, the exchanger HX2 is a favorable case for performance modification.

Nomenclature

e	Specific flow exergy (kJ/kg mole)
Ex	Exergy (kW)
$\dot{E}$	Exergy rate (kW)
$\dot{m}$	Mass flow rate (kg mole/s)
h	Enthalpy (kJ/ kg mole)
P	Pressure (kPa)
T	Temperature (°C)
W	Work (kW)

s	Entropy (kJ/ kg mole.°C)
ε	Efficiency (%)
$\dot{C}$	Cost rate ($/h)
c	Unit average exergy cost ($/Gj)
r	Relative cost difference (%)
f	Exergoeconomic factor (%)
$\dot{Z}$	Investment cost ($)
Subscripts	
C	Cold
H	Hot
Tot	Total
D	Destruction
p	Product
F	Fuel
k	kth equipment
Superscript	
ph	Physical
ch	Chemical
AV	Avoidable
UN	Unavoidable
EN	Endogenous
EX	Exogenous
Abbreviations	
APCI	Air Products and Chemicals, Inc.
C3MR	Propane precooling
DMR	Dual mixed refrigerant
LNG	Liquefied natural gas
MFC	Mixed fluid cascade
NGL	Natural gas liquids
NG	Natural gas
NRU	Nitrogen Rejection Unit
NLP	Non-Linear Programming
PSO	Particle Swarm Optimization
SMR	Single Mixed Refrigerant
ASU	Air separation unit
Names Used for Blocks in Plants	
Ci	Compressor
Exi	Turboexpander
Ti	Tower
HXi	Multi-stream heat exchanger
Di	Flash drum
Vi	Valve
ACi	Air cooler

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