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Identification of the Sources of Energy Loss through Exergy Analysis: Case Study of Marun Mega-Olefin Plant

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Abstract: One of the industries with high potential for energy saving is the petrochemical industry. Ethylene and propylene production plants (olefin plants) – as a part of the petrochemical industry – are very energy intensive. So, any try to improve their energy consumption efficiency could lead to a high amount of energy saving. Iran's petrochemical industry uses old technologies and components and due to sanctions, it couldn't be improved. The main idea of this paper is to improve the energy consumption of one of the biggest petrochemical plants in Iran. So, Marun olefin plant in Iran has been simulated as a case study and its different parts have been analyzed from exergy point of view, which shows the most energy intensive components so that we can focus on for improving the plant's energy consumption. The plant has been divided into three sections and simulated using Aspen HYSYS process simulation software. Then, it has been analyzed using exergy analysis. Results show that the hydrogenation and separation section consisting of many different components has the highest exergy destruction rate and the highest potential for energy saving. Compression section and refrigeration system having compressors are the other parts highly destroying exergy respectively. The causes of exergy destruction for each component has been analyzed and recommendations have been proposed as well.

keywords: Olefin, Ethylene Plant, Exergy Analysis, Exergy Destruction, Exergetic Efficiency

1. Introduction

Energy consumption is one of the major concerns in many processes. According to a study in the United States (Doe, 2006), ethylene producing process is one of the processes with the highest exergy loss. Retrofitting the process is a way to reduce energy consumption and exergy loss. Energy and exergy analysis are two main ways of improving the energy consumption of a process.

Energy analysis is based on the first law of thermodynamics considering the quantity of energy and energy conservation whereas exergy analysis is based on first and second laws of thermodynamics and considers the quantitative measures of the quality of energy transferring within the process and between the process and the environment.

Exergy could be defined based on the second law of thermodynamics as the maximum obtainable work from a given form of energy relative to a reference state called environmental state (Kotas, 1985b). Exergy analysis is a tool for identifying the part of a system with the highest exergy loss. Doing exergy analysis for ethylene plant could lead to an overview of the plant's components performance and help to prioritize plant sections for more evaluation and improvement.

Many researchers have been working on different parts and sub-units of ethylene plant so as to reduce its energy consumption. There have been researches working on different parts of the ethylene plant trying to reduce energy consumption by optimizing their operating conditions like pressure and temperature (Castillo & Dhole, 1995). Others have been trying to improve plant operation

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proposing new design and structure for some parts such as furnaces, distillation columns or refrigeration system (Cooke & Parizot, 2014; Hirata & Kakiuchi, 2011; Hirata, 2010). other researchers have concentrated on exergy analysis looking for sources of exergy losses, especially in the low- temperature refrigeration system (Ataei, 2011; Chang, 2001.; Mafi, Naeynian, & Amidpour, 2009). Environmental issues of these plants with a high amount of energy consumption have been important concern encouraging researchers to analyze it, find pollutions and give the advice to get rid of them (Ghannadzadeh & Sadeqzadeh, 2016; Jozi, Esmat Saatloo, & Javan, 2014).

In this paper it is tried to do exergy analysis on all parts of one of the operational mega-olefin plants of Iran – Marun ethylene plant, calculate the exergy loss of all parts and components, compare them and find the sources of the highest losses.

2. Plant Description

Marun ethylene plant with a capacity of 1100000 tons of ethylene is one of the biggest ethylene recovery plants in the world. It is designed and licensed by Linde Group and uses ethane as a feed which is recovered at ethane recovery plant and is sent to the olefin plant. Marun ethylene plant consists of four sections: cracking and quenching, compression, hydrogenation, and separation train and cascade refrigeration system. A schematic of the ethylene plant can be seen in figure 1.

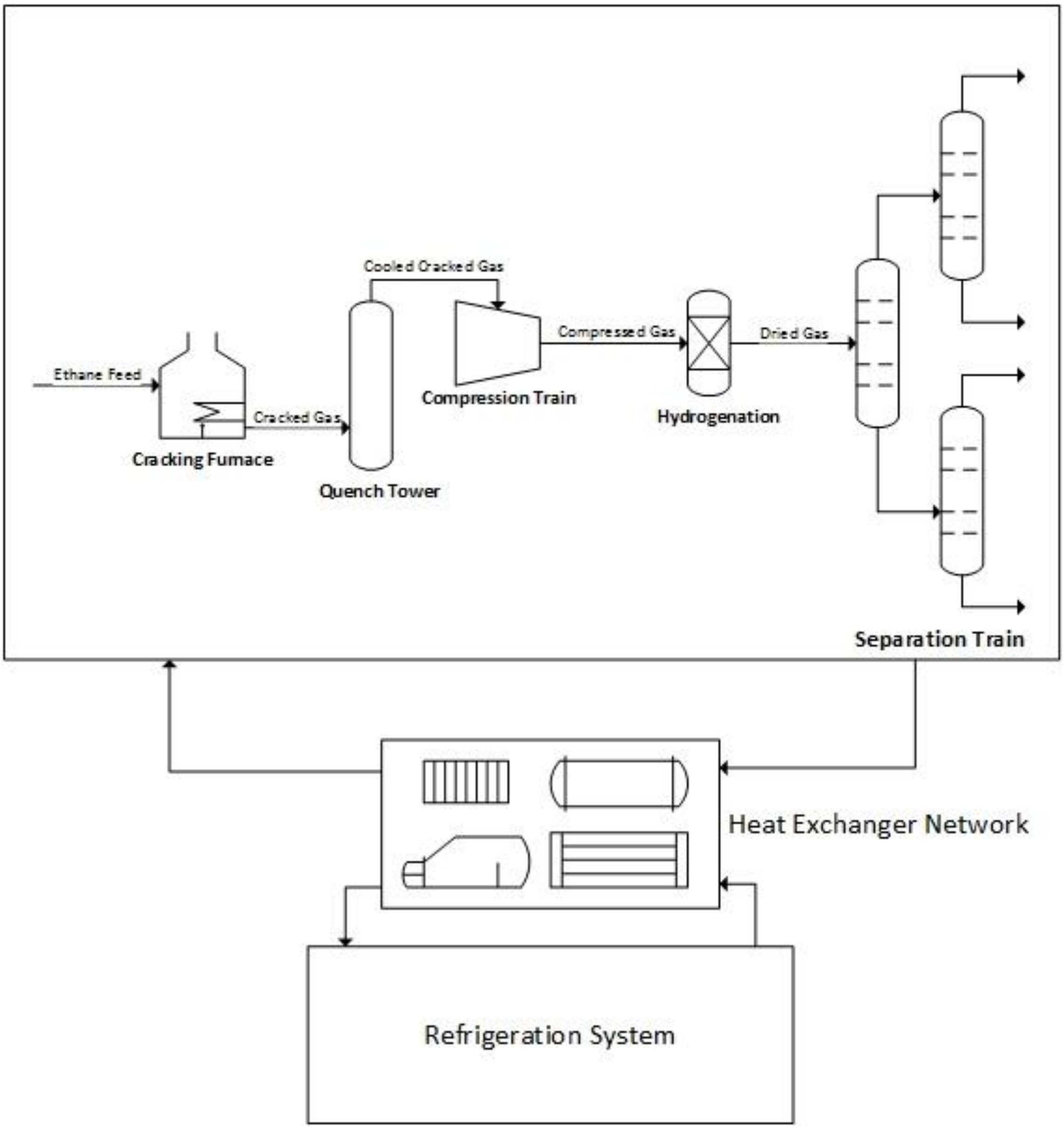

Figure 1. Schematic of Marun ethylene plant

As it can be seen from figure 1, ethane as feed enters the cracking furnace in which it cracks into ethylene and other various products. Cracked gases leaving the furnace must be cooled immediately in order to preserve the current composition of the gas and prevent undesirable side reactions from taking place. The quench tower uses quench water to cool cracked gas leaving the furnace. After the cracked gas has been cooled in the quench tower, the next step in the process is cracked gas compression. A turbine driven centrifugal compressor is utilized to perform this compression and there are five stages, with intermediate cooling compressing the gas from 1.4 bar to 37 bar. The cracked gas is saturated with water before compression and after each intercooler stage. Moisture must be removed before fractionation to prevent the formation of hydrates and ice. Drying is arranged before the first fractionation step, after the last compression stage. Multiple adsorption beds make continuous water removal possible. In this unit, acetylene formed through the cracking process is changed to ethylene and propylene. Also, other unsaturated molecules like MAPD and butadiene are hydrogenated. The fractionation section receives the compressed cracked gas at a pressure of 464 to 551 psi (32-38 bar) for further fractionation into different products and fractions at specified qualities. This is done through a series of distillation columns. The following is a listing of the various distillation columns and their functions (“Ethylene Production,” 2010):

Deethanizer: acetylene, ethylene, and ethane are separated from the top as overhead componentsfrom C3+ as bottom components.

Depropanizer: Separates propane and lighter components from C4+ fractions.

C2 splitter or ethylene fractionation: Ethylene fractionation separates ethylene as a high-purity overhead product from ethane, which is combined with propane and recycled for cracking.

C3 splitter or propylene fractionation: Propylene fractionation separates propylene as a chemical grade overhead product or more frequently as polymer grade propylene from propane. Propane is recycled for cracking.

Ethylene refrigerant system supplies the reflux stream of C2 splitter, cooling demand of some parts of the process and compressed ethylene for different needs in the plant. Ethylene is supplied in three different pressures and temperatures. Low pressure at -100°C, medium pressure at -80°C and high pressure at -56°C. Four stages compressor compresses ethylene vapor getting its power from a steam turbine. Propylene refrigeration cycle is used for cooling at medium temperatures. The propylene refrigerant supplies cooling in three levels: Low- pressure propylene at -38°C, Medium pressure propylene at -16°C, High- pressure propylene at 10°C. Propylene vapor is compressed in a three stages compressor.

The plant was simulated using Aspen HYSYS 8.4 process simulation software, a powerful tool for simulating complex chemical and petrochemical processes. Peng–Robinson–Stryjek–Vera (PRSV), a common fluid package for simulating chemical and petrochemical plants, has been selected for predicting stream properties (Ansarinasab, Afshar, Mehrpooya, & Energies, 2016; Tirandazi, Mehrpooya, Vatani, & Moosavian, 2017). Atmospheric conditions considered are 1 bar and 40° C, the condition of Bandar-E-Imam’s weather. All streams and components were simulated and simulation results were used for exergy analysis. It should be noted that the cracking and quenching section was not considered in this study. Figures 2-4 show the schematic of the compression, hydrogenation and separation and refrigeration system, which were simulated analyzed using exergy analysis.

The simulation was compared to the Process Flow Diagram (PFD) of the plant so as to validate the results and consequent exergy analysis be reliable. Table 1 shows the validation for the temperature and pressure of some important streams in the plant.

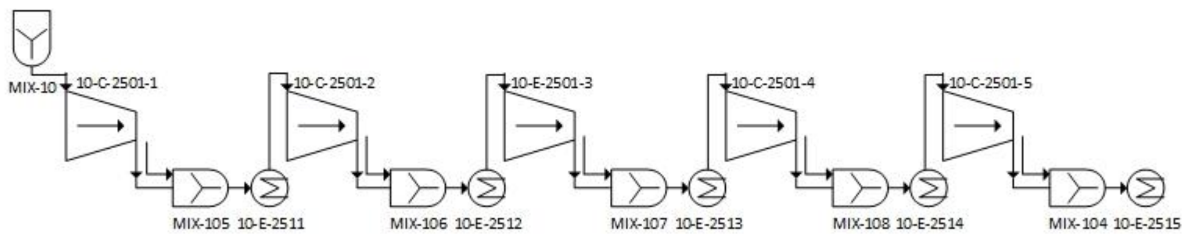

Figure 2. A schematic of compression train

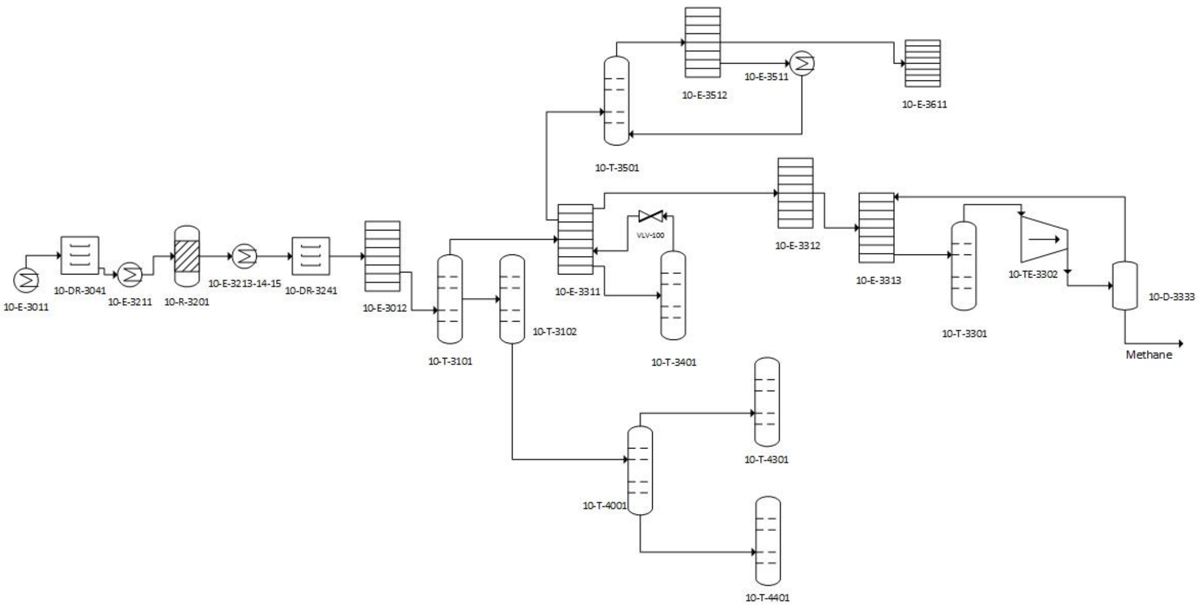

Figure 3. A schematic of separation section

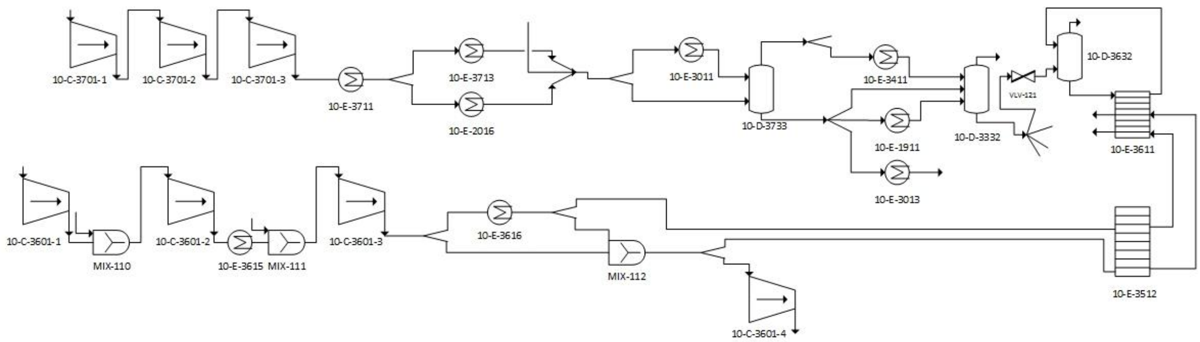

Figure 4. A schematic of the ethylene and propylene refrigeration systems

Table 1. Validation results for some important streams in the plant

stream	T (^{0}C) Sim.	P (bar) Sim.	T (^{0}C) PFD	P (bar) PFD	T Error (%)	P Error (%)
23-21	42.78	1.5	40.98	1.5	4.4	0
26-1	33.09	19.7	32.41	19.8	2.1	0.5
26-3	35	19.20	35	19.25	0	0.2
30-41	13.84	35.7	14.87	35.85	6.9	0.4
32-8	96.4	32.75	92.47	34.65	4.25	5.5
31-9	-13.98	26	-13.12	26	6.55	0
34-4	-4.53	31.9	-4.47	31.9	1.34	0

3. Exergy Analysis

Exergy indicates that how far a system is from the reference state which is called dead state. Dead state is an environmental condition (Vatani, Mehrpooya, & Palizdar, 2014). The exergy of a system is often divided into four components. the common ones are physical exergy and chemical exergy(Kotas, 1985b). The two others, kinetic, potential and are assumed to be negligible here.

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

Physical exergy is defined as the maximum obtainable work from a system when it is taken to the physical equilibrium with the environment and can be calculated from equation (2) (Kotas, 1985b).

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

In which h and s are the enthalpy and entropy of the system at its own temperature and pressure respectively and h_0 and s_0 are the enthalpy and entropy of the system at the environmental temperature and pressure respectively.

Chemical exergy is the maximum obtainable work from a system when it is taken from environmntal conditions to the desired state through heat transfer and material exchange (Kotas, 1985b). Chemical exergy can be calculated from equation (3) (Vatani et al., 2014).

$$e_{ch} = \Sigma x_i e_i^0 + G - \Sigma x_i G_i \quad (3)$$

In which x_i and $e_i^0$are mole fraction and standard chemical exergy of the i-th component respectively. G is the total Gibbs free energy and G_i is the Gibbs free energy of i-th component at the environment temperature and pressure.

Two important parameters obtained from exergy analysis are exergy destruction and exergetic efficiency which are calculated from equations (4) and (5) and (6).

$$\dot{E}_D = \dot{E}^{in} - \dot{E}^{out} + \dot{E}^{Q} - \dot{E}^{W} \quad (4)$$

Where $\dot{E}_D$ is the total irreversibility rate, $\dot{E}^{in}$ and $\dot{E}^{out}$ are exergy rate entering and exiting the system as material streams,$\dot{E}^{Q}$ and $\dot{E}^{W}$ are the exergy transfer rate accompanying heat transfer and work transfer respectively.

$$\varepsilon_i = \dot{E}_{product}/\dot{E}_{fuel} \quad (5)$$

$$\varepsilon_i = 1 - \dot{E}_D/\dot{E}_{fuel} \quad (6)$$

Where $\varepsilon_i$is the exegetic efficiency, $E_{product}$ is the exergy of product stream of the plant component and E_{fuel} is the exergy we spend to get what we expect.

Table 1 shows the exergy balance and exergetic efficiency equations for the plant components.

It is noteworthy that however the exergetic efficiency of a heat exchanger is defined as the proportion of the increase of the cold stream's exergy to the decrease of the hot streams exergy(Kenneth Wark Jr, 1995), because most of the temperature of the streams below the environment temperature the exergetic efficiency of such heat exchangers is defined as the proportion of the increase of the hot stream's exergy to the decrease of the cold streams exergy. Also, the sign of the exergies of the reboiler and condenser depends on the temperature in which reboiler and condenser operate.

In this work, a code was developed in MATLAB programming language for calculating physical, chemical and total exergies. MATLAB and HYSYS softwares were linked together so that MATLAB can get necessary stream data for calculating exergy of each process stream. the results were used for determining exergy destruction and exergetic efficiency of each plant component. Figure 2 shows a flowchart of exergy analysis.

Table 2. Exergy balance and exergetic efficieny definition for each plant component(Kotas, 1985a)

Components	Exergy destruction	Exergetic Efficiency
Compressors	$\dot{E}_i - \dot{E}_o + \dot{W}_{comp}$	$(\dot{E}_o - \dot{E}_i) / \dot{W}_{comp}$
Separators	$\Sigma\dot{E}_i - \Sigma\dot{E}_o$	$\Sigma\dot{E}_o / \Sigma\dot{E}_i$
Mixers	$\Sigma\dot{E}_i - \Sigma\dot{E}_o$	$\dot{m}_2(e_3 - e_2) / \dot{m}_1(e_1 - e_3)$
Heat Exchangers	$\Sigma\dot{E}_i - \Sigma\dot{E}_o$	$(\dot{E}_o - \dot{E}_i)_{hot} / (\dot{E}_i - \dot{E}_o)_{cold}$
Multi-Stream Heat Exchangers	$\Sigma\dot{E}_i - \Sigma\dot{E}_o$	$(\Sigma\dot{E}_o - \Sigma\dot{E}_i)_{cold} / (\Sigma\dot{E}_i - \Sigma\dot{E}_o)_{hot}$
Reactor	$\dot{E}_i - \Sigma\dot{E}_o$	$\dot{E}_o / \dot{E}_i$
Columns	$\Sigma\dot{E}_i - \Sigma\dot{E}_o$	$1 - (\dot{E}_D/(\dot{E}_{reboiler} - \dot{E}_{condenser}))$
Splitters	$\dot{E}_i - \Sigma\dot{E}_o$	$\Sigma\dot{E}_o / \dot{E}_i$
Valves	$\dot{E}_i - \dot{E}_o$	$\dot{E}_o / \dot{E}_i$

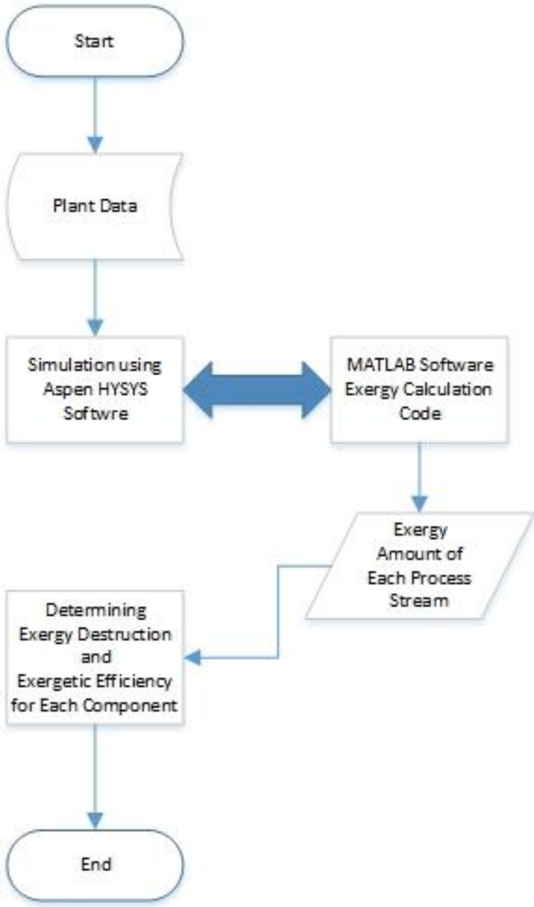

Figure 5. Flowchart of exergy analysis

4. Results and Discussion

4.1. Compression

Figure 6 shows the exergy destruction for each component of the compression section. Different stages of the compressor have a high level of exergy destruction. Doubling the pressure in each stage with a consequent rise in temperature, are the main sources of exergy destruction in the compression section. Exergy loss of the compressors can be reduced by lowering the inlet temperature, but this can lead to condensation of the inlet stream that is very dangerous for the compressor's blades. However, drums before the compressor inlet prevent the liquid from entering the compressor. Another advice is increasing the compressor's efficiency by isolating it or changing some pieces to more efficient ones. Intercoolers have high exergy destruction as well. This is mainly because of the high-temperature difference and high heat exchange rate. The temperature difference between the hot stream and the cooling water source reaches approximately 45° C which is a relatively high difference considering hot stream with a high mass flow rate to be cooled. Pressure drop in coolers is another source of exergy destruction. Mixing the streams with different conditions and compositions causes the exergy destruction in mixers. Trying to reduce temperature and pressure difference between streams need to be mixed, prevent exergy destruction level of these components to be high.

Figure 7 illustrates the exergetic efficiency of the compression section's components. Improving exergetic efficiency of the compressor using the ways mentioned before can lead to a considerable reduction of exergy destruction of this section. Intercoolers have low exergetic efficiency which is partly because of the limitation of the cooling source and partly because of design and pressure drop. Lowering the load of coolers and lowering the pressure drop can increase the efficiency and reduce the exergy destruction. Exergy destruction of intercoolers reduces from the first stage to the last stage due to the reduction of heat exchange load resulted from using the cold stream with lower mass flow rate. So, the efficiency is increased from the first cooler to the last one.

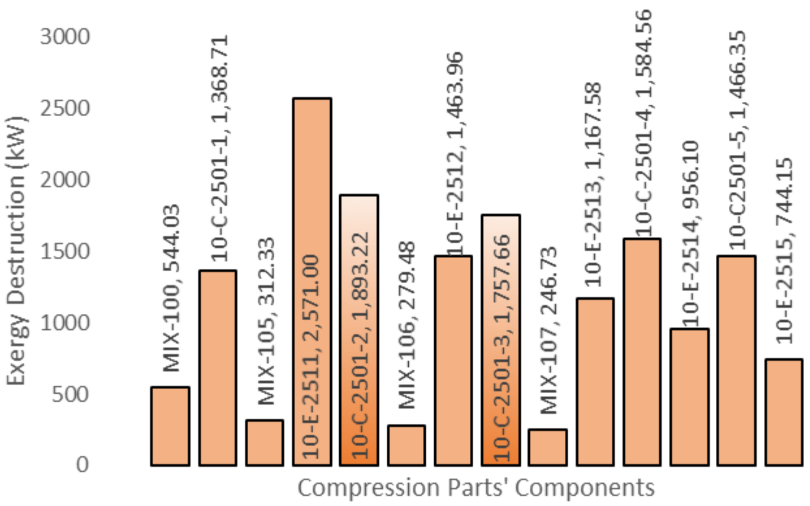

Figure 6. Compression section exergy destruction

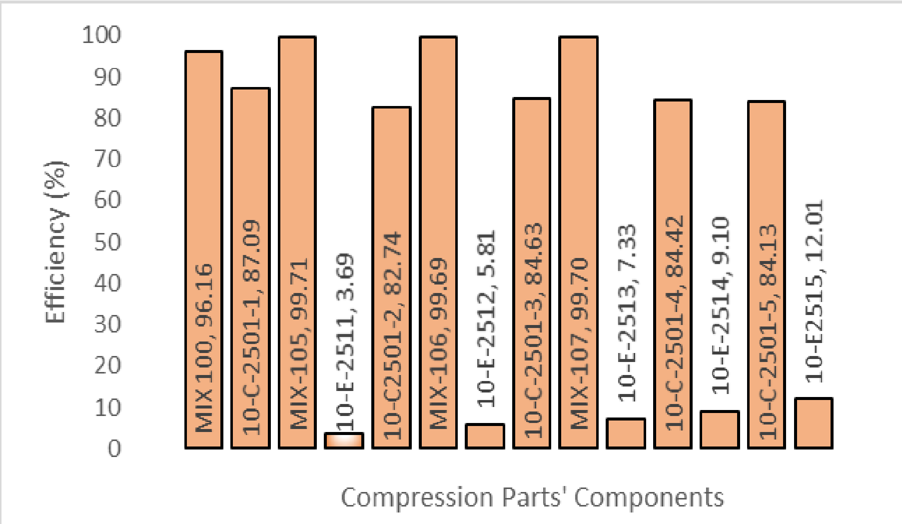

Figure 7. Compression section exergetic efficiency

4.2. Hydrogenation and Separation Sections

Exergy destruction of some of the components of this section with high loss can be seen in figure 8. As the figure indicates, the highest exergy destruction occurs in the reactor because of the exothermic reaction. Due to the nature of the reaction, this exergy destruction cannot be prevented. However, it can be reduced somehow through some structural changes in the reactor or some changes in controlling the reaction process (Leites, Sama, & Lior, 2003). Also, using catalyst particles with a special shape for reducing pressure drop could be helpful for lowering exergy loss. Towers show the high rate of exergy destruction. Towers get a high rate of heat in their reboilers and deliver lots of it to the environment in their condensers. In other words, the high- temperature difference between bottom and top of the column is one of the main sources of exergy destruction in columns. For example, in deethanizer 10-T-3102, the bottom temperature is about 77° C while the temperature at the top is as low as -13° C which reaches to -31° C after condenser. This makes a high exergy destruction rate in the towers. It should be noted that towers with no condenser such as 10-T3101 and 10-T-3401 have low exergy destruction. The other sources of exergy destruction in columns are the pressure drop and concentration difference between inlet and outlets. Reducing each of these sources could lead to lower exergy loss and higher efficiency of the towers. Some structural or operational changes or rearrangements in design could be considered in this regard as suggested in (Alhajji & Demirel, 2016; Veiskarami & Rahimi, 2014). Multi-stream heat exchangers like 10-E-3012, 10-E-3312, 10-E3313 ,and 10-E-3512 with high- temperature differences and high-pressure drop as the causes of exergy loss, show high levels of loss. This could be reduced considering design factors for eliminating those causes as much as possible. Valve VLV-100 has high exergy loss due to the high level of pressure drop which is approximately 21 bar. Because the stream entering the valve is in a liquid phase, it can not be used for power generation in a turbine.

Figure 9 demonstrates the exergetic efficiency for the components of this section. Multi-stream heat exchangers and towers have relatively lower exergetic efficiency in comparison to other components. This could be increased as discussed before using some structural or operational changes.

4.3. Refrigeration System

As one can find out from figure 10, compressors of the refrigeration system that provides refrigeration in different pressure, show a high rate of exergy destruction. The third stage of the ethylene refrigeration system has a considerable exergy loss in comparison to other stages because of a higher pressure difference. Ethylene compressor, except for the last stage, have lower exergy loss in comparison to propylene compressor as a result of higher efficiency. As mentioned in section 4.1, this exergy destruction in compressors is due to the pressure and temperature difference between inlet and outlet and could be reduced using isolation and replacing some parts with more efficient ones. Coolers 10-E-3711, 10-E-3615 , and 10-E-3616 deliver a high rate of exergy to the environment and have high exergy destruction. High- temperature difference and pressure drop are the main sources of exergy destruction in these heat exchangers. This can be reduced by reducing outlet temperature of the compressors which could be reached through increasing adiabatic efficiency. Reducing pressure drop helps lowering exergy destruction in heat exchangers as well. Exergy destruction observed in drums 10-D-3732 and 10-D-3733 is a result of the throttling process in separators which is accompanied by changes in temperature and pressure between inlet and outlet.

Figure 11 indicates that propylene refrigeration system's compressor has relatively high exergetic efficiency comparing it with ethylene refrigeration system's compressor. Intercoolers between stages of compressors have low exergetic efficiency and need to be modified structurally or operationally so that their sources of exergy loss, which are a high- temperature difference and high- pressure drop, be reduced.

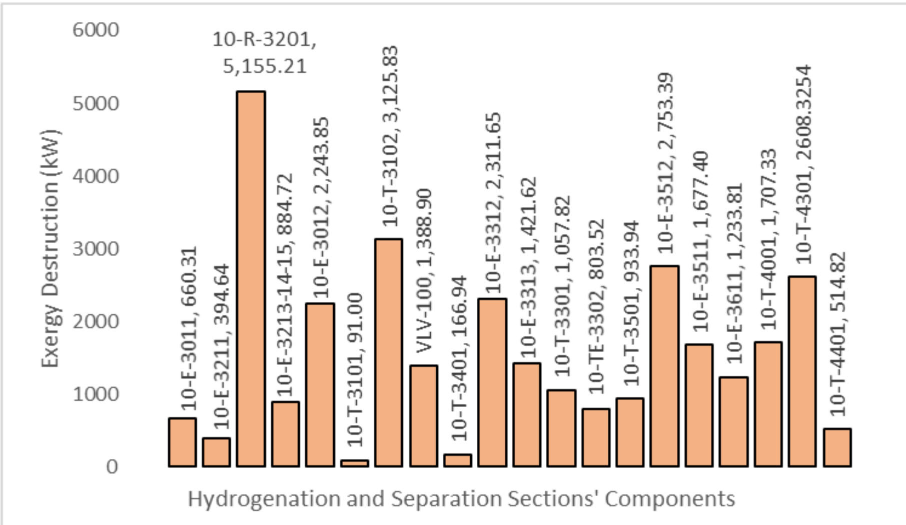

Figure 8. Hydrogenation and separation sections exergy destruction

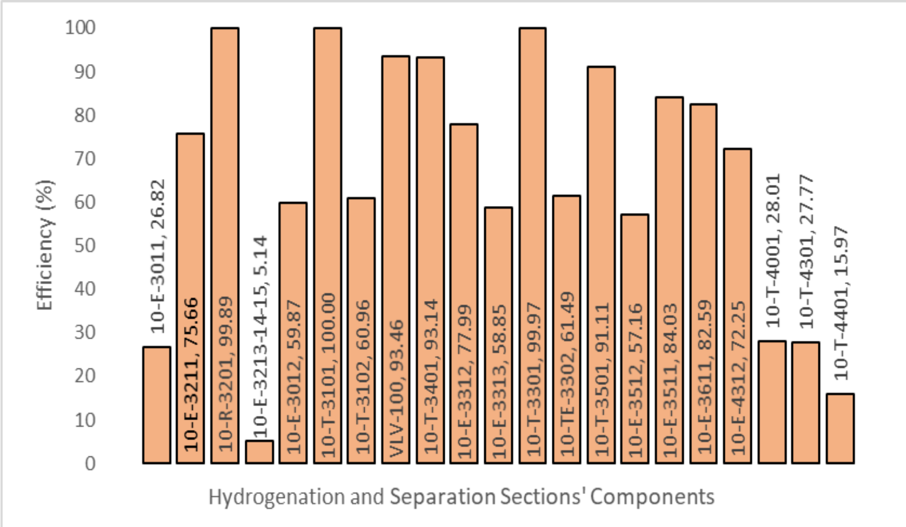

Figure 9. Exergetic efficieny of the hydrogenation and separation sections's components

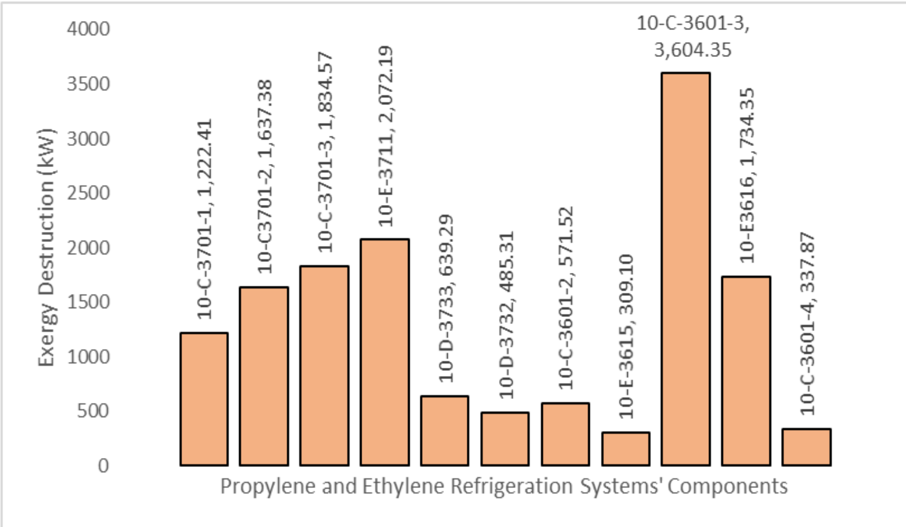

Figure 10. Refrigeration system components' exergy destruction

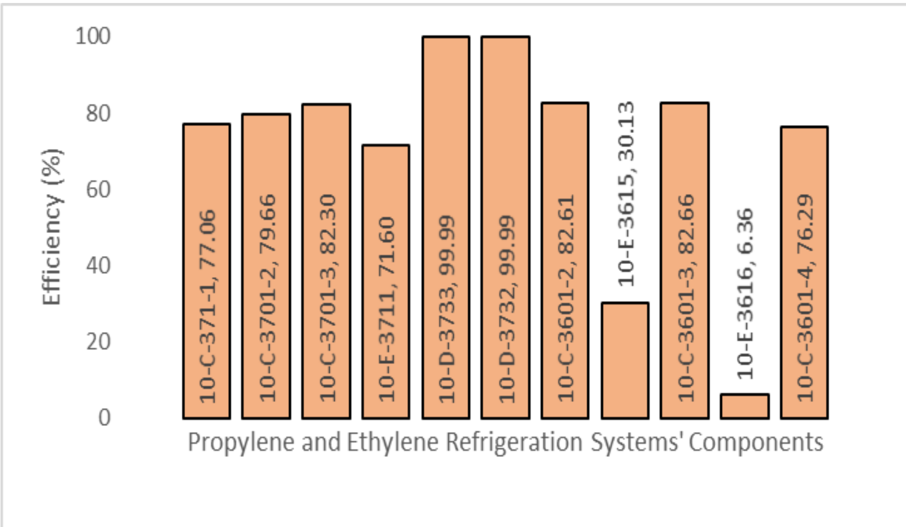

Figure 11. Refrigeration section exergetic efficiency

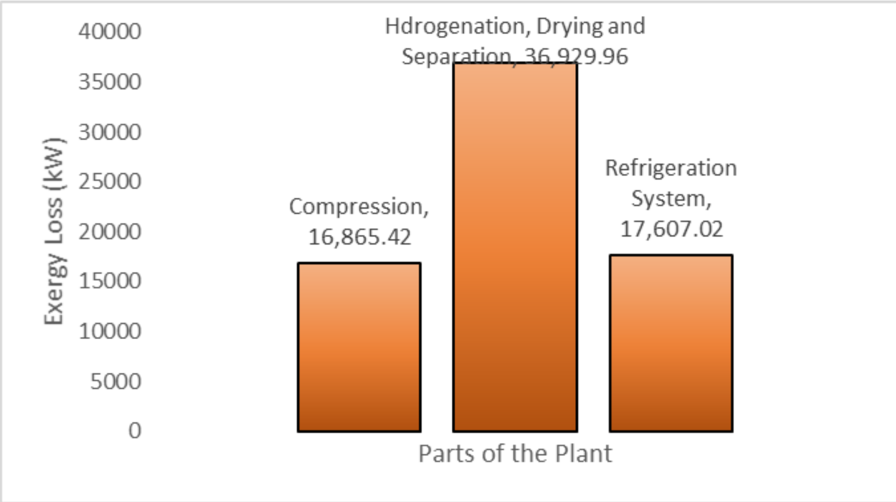

Figure 12. Comparing exergy destruction of different parts of the plant

4.4. Comparing three Sections

Figure 12 demonstrates the exergy destruction of the sections analyzed in this work. As it can be seen hydrogenation and separation part has the highest exergy destruction. Most of the components of the plant are in this part and the numbers of components in comparison to other parts make the exergy destruction of this part to be higher. Reactor along with the towers consume a huge amount of energy in their reboilers and delivering most of it to the environment in their condensers play important role in wasting energy in this section. Also multi-stream heat exchangers of this section waste lots of energy. The refrigeration system is the second section, but its exergy destruction is near to the compression part. The compressors of the refrigeration system destroy lots of exergy through pressurizing the refrigerant and because of the relatively low efficiency resulted from the waste of energy through compressor casing to the environment. Compression train pressurizing the cracked gas for fractionation is the last section with high exergy destruction amount. This is mainly because of high - pressure difference and coolers with high heat transfer load and high- temperature difference.

5. Conclusion

One of the most energy- intensive industries is chemical and petrochemical industry. Due to its wide range of application, ethylene production is the heart of petrochemical production. In this paper, one of the Iranian mega-olefin plants – Marun ethylene plant – was considered as the case study for exergy analysis. The plant, except for cracking section, was divided into three section namely compression section, hydrogenation and separation, and refrigeration system and it was simulated using Aspen HYSYS process simulation software. By developing a code for exergy analysis in MATLAB programming language and linking it with Aspen HYSYS exergy analysis was carried out. Results indicated that hydrogenation and separation section has the highest exergy loss among others with an exergy destruction about 36930 kW. The second section with a high level of exergy destruction was compression section having an exergy destruction about 21792 kW and the last section was refrigeration system that showed a level of destruction about 17607 kW. There is a high level of exergy destruction in the plant which needs to work on for reducing. The main source of exergy destruction in compression section was the compressor pressurizing the cracked gas to a high- pressure level for fractionation. This source could be reduced isolating the compressor's casing to prevent losses, using more efficient components and reducing inlet temperature as much as possible. The other high level of exergy destruction in this section belonged to intercoolers with the high duty, temperature difference and pressure drop which need to be improved. Reactor, distillation columns and multi-stream heat exchangers have a significant share of exergy destruction of the hydrogenation and separation section. Reactors exergy destruction is somehow intrinsic because of the exothermic reaction occurring, but there are still some works that can be done for reducing exergy destruction such as controlling the conditions of the reaction and using some catalysts with a low- pressure drop. Distillation columns getting a huge amount of energy in reboiler and delivering lots of energy to the environment in the condenser have high exergy destruction as well. Trying to enhance trays' efficiency, modifying the arrangement of the separation columns and reducing the temperature difference driving force helps to reduce the exergy destruction. Multi-stream heat exchangers with high heat exchange load, high- temperature difference , and pressure drop destroy loss of exergy. Reducing each of these will reduce the heat exchangers' exergy destruction. Compressors are responsible for the high exergy destruction of the refrigeration section that could be improved using advice mentioned for the compression section before. Finally, more advanced analysis and optimizations are recommended for having a better view of the sources of energy loss and modifying the plant.

Acknowledgement

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Nomenclature

T	Temperature
h	Enthalpy
s	Entropy
$\dot{W}$	Power
ε	Exergetic efficiency
P	Pressure
HE	Heat Exchanger
in	Inlet
out	Outlet
e^{ph}	Physical Exergy
e^{ch}	Chemical Exergy
e^{tot}	Total Exergy
G	Gibbs Free energy
x	Molar Fraction
$\dot{E}$	Exergy Rate
$\dot{E}_D$	Exergy Destruction

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