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ADVANCED EXERGETIC ANALYSIS OF PREHEAT TRAIN OF A CRUDE OIL DISTILLATION UNIT

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ABSTRACT

In this investigation, the conventional and advanced exergy analysis is used to obtain information about the conditions of the heat exchangers belonging to a crude oil distillation unit, previously to future studies to establish the most cost-efficient moments for the execution of maintenance activities in the exchangers. Conventional, unavoidable, avoidable, endogenous, and exogenous exergy destruction is calculated and the combinations between these last four terms. Mexogenous analysis is applied to individualize the relationships between the exchangers of the network. The results put the total exergy destruction at over 61.6 MW, being 63% avoidable. Five heat exchangers are considered critical because they concentrate the highest rates of exergy destruction, corresponding to 39% of the total exergy destruction in the network, this categorization allows focusing the improvement works on heat exchangers that will produce a substantial increase in the efficiency of the preheat train. Additionally, to evaluate the performance in a better way, the effect of unavoidable exergy destruction on performance measurement of exchangers through the exergy efficiency is studied, indicating that in some cases removing the unavoidable part can increase the second law efficiency by more than fifteen percentage points.

Keywords:Advanced Exergy Analysis,Exergy destruction, Heat Exchanger, Preheat Train, Crude Oil Distillation Unit.

1. INTRODUCTION

The increase in energy demand, associated costs, and environmental effects have turned efficiency into one of the most important parameters for industries [1], [2]. The petrochemical sector is known for presenting high levels of energy consumption, being the processing of crude oil in distillation units (CDU) one of the processes with the highest energy consumption, reaching values of 30349,01(10^4 GJ) due to the large amounts of heat required to fractionate the oil [3], [4].

To reduce the heat provided by the furnace, heat exchanger networks (HEN) are used to take advantage of residual heat of products coming from the distillation tower to increase the temperature of crude oil before it enters the furnace. However, factors such as aging, oil composition, and fouling affect the performance of the exchangers, causing a higher fuel consumption in the furnace and consequently a decline in the efficiency of the unit [5]-[8].

To develop methods focused on improving the performance of processes or equipment, it is necessary to do previous studies to determine the relationships between the plant components, their operating conditions, and other factors that can generate energy losses. In the case of CUD, studies based on the second law of thermodynamics are proposed to find sources of inefficiency, allowing the establishment of hierarchies according to the repercussions of each one [9].

Nur Izyan and Shuhaimi [10] use exergy analysis as a strategy for reduction of fuel consumption in a crude oil distillation unit. As they observe that the largest exergy loss occurs inside the furnace, they propose two options for its reduction: first, focused on reducing heat loss in the furnace stack, and second, based on increasing the furnace inlet temperature. They suggest then, to establish optimal cleaning schedules to heat exchangers, but the fact that their considerations are related to the total exergy destroyed does not represent a clear view about the opportunity for improvement in the plant, because in a real process there will be a portion of exergy destruction of unavoidable type.

A fairer evaluation of assets involves the consideration that due to limitations in manufacturing processes, their operating and environmental conditions is impossible to reduce the exergy destroyed to zero; consequently, the unavoidable exergy destruction is the irreversibility of the equipment that cannot be eliminated by any of the reasons expressed above [11].

Focusing on exergy destruction that can be avoided allows categorizing the intervention priority more adequately, as established by Fajardo et al. [12] in their study about unavoidable and avoidable exergy destruction in a nitric acid plant. Their results place the exergy destroyed in the order of 46772 kW, being 75.1% avoidable. They also recommend directing the improvement tasks to the catalytic converter (critical asset) because it represents more than 75% of all avoidable exergy destruction.

The importance of identifying critical equipment in a heat exchangers network is referred to by Samïli et al. [13], who tried to reduce the level of fouling through nonlinear programming to establish the right times to do maintenance activities, observed how some exchangers had an extremely higher effect within the network, naming them "key heat exchangers".

An exergy study of a natural gas refinery exchanger network by Fard and Pourfayaz [14] shows that 59% of exergy destruction can be avoided, which would represent an increase from 62,8% to 84,2% in exergy efficiency of the network. The investigation also connects the "key heat exchangers" with their effect within the network, for the specific case, 18 exchangers (17% of all) represent 61% of total exergy destruction.

Rivero et al. [15] incorporate an estimate called "exergy improvement potential" through the relationship between the irreversibilities of the equipment and its effectiveness, to determine in which elements of the system are much better to do optimization work. The evidence indicates that in the crude oil distillation unit, the atmospheric distillation section has the highest rate of exergy destruction and consequently leads to the costs due to losses but at the same time it is also the section of the plant with the highest potential for improvement.

However, the considerations made above are conditioned because the investigations evaluate each element independently from the rest of the elements of the system, it is not enough to know the amount of exergy destroyed that can be recovered from equipment because this can be caused by two types of irreversibility: the first is that which occurs within the component to be considered and the second is external irreversibilities coming from remaining equipment, for example, Wang et al. [16] identified that a part of the exergy destruction generated in the turbines of a power plant is caused by the malfunction of other elements.

This study proposes not only to identify the amounts of unavoidable and avoidable exergy destruction but also to individualize its origin through an exhaustive analysis to determine the equipment-to-equipment relationships along with the entire heat exchanger network, obtaining a clearer and more realistic view of the plant for future optimization or scheduling of maintenance activities with better cost-benefit ratios.

2. MATERIALS AND METHODS

The preheat train (PHT) belongs to a crude oil distillation unit designed to operate 150,000 barrels per day (150,000 BPD). The production process consists of circulating the crude oil through the HEN before it reaches the furnace where it is heated to temperatures reaching 371 °C to be fractionated into different products: heavy vacuum gas oil (HVGO), medium vacuum gas oil (MVGO), atmospheric gas oil (AGO), heavy diesel (HDIESEL) and vacuum residue (VR).

Since the oil temperature difference between the inlet of the unit and the outlet of the furnace is around 339 °C, is convenient to use preheat train as a regenerative process to increase the plant's energy efficiency, reduce operating costs and environmental impact.

Figure 1 schematically represents the atmospheric distillation section of the plant, which consists of three elements: the heat exchanger network, the furnace, and the distillation column. The PHT is confirmed by twenty-five shell and tube heat exchangers, connected in series and parallel, to reduce the heat input required in the furnace, where the fractions obtained by distillation transfer heat to the oil (red lines in Fig. 1), which will enter at the furnace.

As already mentioned, this process has a positive impact on fuel consumption and therefore on operating costs and environmental impacts, but it also has an impact on the operating cost of products because if the train is not used, another process should be implemented to reduce their temperature before they are stored or transported.

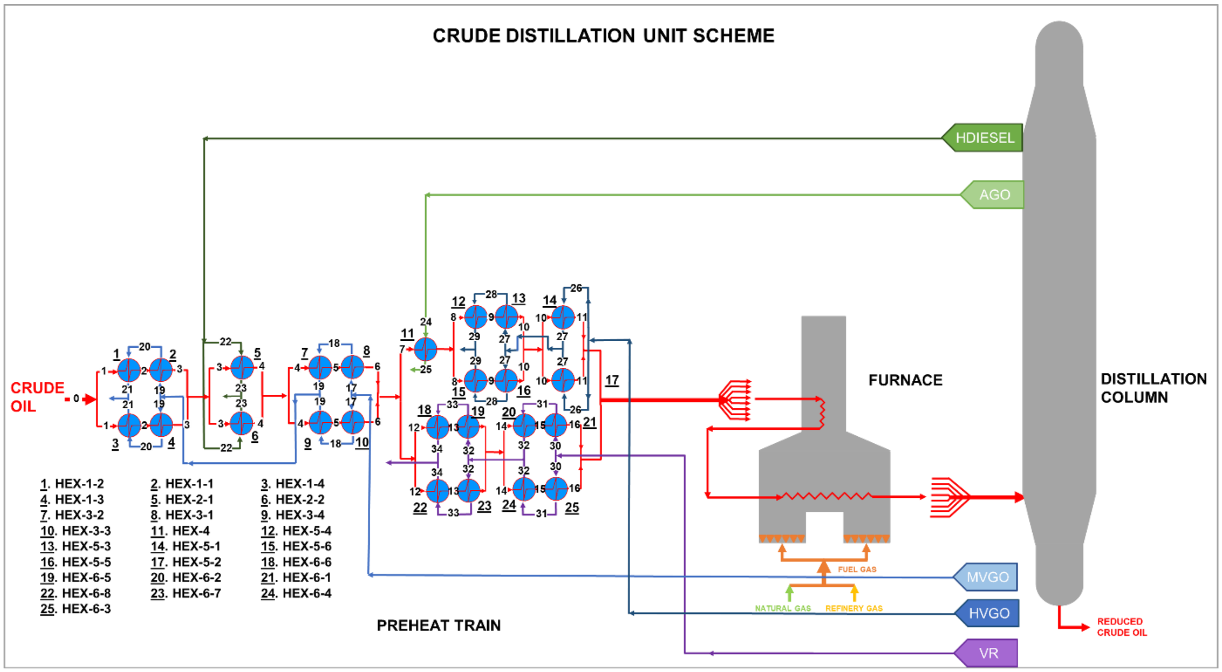

FIGURE 1: SCHEME OF PREHEAT TRAIN OF THE CRUDE DISTILLATION UNIT [17].

2.1 Thermodynamic properties

The heat capacity at constant pressure (C_p) is the starting point to obtain other properties of fluids involved, for the case of crude oil there are several models for its calculation as a function of temperature, in this research the equation (1) proposed by Polley [18] was used because it provides a better fit with the operating data of the PTH under study [17].

$$C_{p_{crude\ oil}} = (3T + 1940)10^{-3} \tag{1}$$

The API standard "Technical Data Book- Petroleum Refining" [19], used in [20], [21], [21] allows to calculate the $C_p$of fractions obtained by distillation, equation (2) is an adaptation of the expression formulated by API to work in units of the international system.

$$C_{p_{fraction}} = 4{,}19 * 10^{-3}[A_1 + A_2(1{,}8T + 491{,}67) + A_3(1{,}8T + 491{,}67)^2] \tag{2}$$

A_1, A_2y A_3 come from equations (3), (4) and (5). These constants are characteristic of the fractions, depending only on the specific gravity, SG, and Watson characterization factor (k_w) used to classify the fractions according to boiling point.

$$A_1 = -1{,}17126 + (0{,}023722 + 0{,}024907SG)K_w + (1{,}14982 - 0{,}046535K_w)SG^{-1} \tag{3}$$

$$A_2 = (10^{-4})(1 + 0{,}82463K_w)(1{,}12172 - 0{,}27634SG^{-1}) \tag{4}$$

$$A_3 = (-10^{-8})(1 + 0{,}82463K_w)(2{,}9027 - 0{,}70958SG^{-1}) \tag{5}$$

According to thermodynamic theory, the enthalpy and entropy associated with the i-th flow in liquid state can be obtained by:

$$h_i \approx C_{p_i} T_i \tag{6}$$

$$s_i - s_0 = \int_{T_0}^{T_i} C_p(T)\frac{dT}{T} \approx C_{p_{avg}}\, ln\left(\frac{T_i}{T_0}\right) \tag{7}$$

2.2 Conventional exergetic analysis

Exergy is considered as the useful energy of a system, it can be expressed as the sum of potential, kinetic, physical and chemical exergies [22].

$$\dot{E}_k = \dot{E}_k^{PT} + \dot{E}_k^{KN} + \dot{E}_k^{PH} + \dot{E}_k^{CH} \tag{8}$$

The change of exergy at any point in the HEN is due to physical changes since there are no chemical reactions, besides the variations of kinetic and potential exergy are negligible. The specific physical exergy of a stream is obtained by:

$$e^{PH} = h_i - h_0 - T_0(s_i - s_0) \tag{9}$$

Second law studies usually classify exergy according to its purpose within a process, those established as desired outputs are categorized as products and those responsible for providing the necessary exergy inputs are called fuel [23], then, the exergy destruction becomes that portion of useful energy that the fuel gave up and was not received by the product. For this investigation, the product exergy is the exergy contained by the crude oil and the fuel exergy is supplied by the hot fluid.

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k} \tag{10}$$

The exergy indicators employed in conventional analysis are: exergy efficiency and exergy destruction ratio [24].

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \tag{11}$$

$$y_k = \frac{\dot{E}_{D,k}}{\dot{E}_{F,Total}} \tag{12}$$

2.3 Advanced exergetic analysis

To calculate the unavoidable exergy destruction $\left(\dot{E}_{D,k}^{UN}\right)$, the element of interest must be separated from the system, and it should be assumed that it operates under the best possible conditions and therefore with the best performance. This allows obtaining a specific unavoidable exergy destruction $\left(\dot{E}_D/\dot{E}_P\right)_k^{UN}$ to be multiplied by the product of the component, and in turn, obtaining the unavoidable exergy destruction according to the real operating conditions [11].

$$\dot{E}_{D,k}^{UN} = \dot{E}_{P,k}\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_k^{UN} \tag{13}$$

The avoidable destroyed exergy) is the part of the exergy destruction remaining after subtracting the unavoidable from the total destroyed exergy.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{UN} + \dot{E}_{D,k}^{AV} \tag{14}$$

Once the unavoidable and avoidable exergy destruction has been identified, it is convenient to use a modification of exergy efficiency (ε_k^*) to prioritize the effect of avoidable exergy destruction on the performance of the component under consideration [11].

$$\varepsilon_k^* = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k} - \dot{E}_{D,k}^{UN}} \tag{15}$$

The endogenous destroyed exergy $\left(\dot{E}_{D,K}^{EN}\right)$ is the useful exergy wasted by an element due to its malfunction, for its calculation, all the remaining components operate in their theoretical condition except for the component under consideration which will be governed by the real efficiency of its process. The exogenous destroyed exergy $\left(\dot{E}_{D,K}^{EX}\right)$, which is caused by the remaining components, is obtained from the difference between the total and endogenous destructions [25].

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{EN} + \dot{E}_{D,k}^{EX} \tag{16}$$

Obtaining the four types of exergy destruction mentioned earlier allows to do better judgments about the optimization potential of a system, which is much more beneficial if these concepts are mixed, as concluded by Kelly et al. [26]. The equations for the calculation of endogenous unavoidable, exogenous unavoidable, endogenous avoidable, and exogenous avoidable exergy destruction shown in equations (17), (18), (19), and (20) come from [27], [28].

$$\dot{E}_{D,k}^{UN,EN} = \dot{E}_{P,k}^{EN}\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_K^{UN} \tag{17}$$

$$\dot{E}_{D,k}^{UN,EX} = \dot{E}_{D,k}^{UN} - \dot{E}_{D,k}^{UN,EN} \tag{18}$$

$$\dot{E}_{D,k}^{AV,EN} = \dot{E}_{D,k}^{EN} - \dot{E}_{D,k}^{UN,EN} \tag{19}$$

$$\dot{E}_{D,k}^{AV,EX} = \dot{E}_{D,k}^{AV} - \dot{E}_{D,k}^{AV,EN} \tag{20}$$

Equations (18) and (20) only provide a general quantification of the effect of irreversibilities from remaining exchangers. A mexogenous analysis allows the identification of specific component(s) and how it affects component k. It is determined by the difference between the exogenous exergy destruction and the combination of the exergy destruction effects of the other components [29].

$$\dot{E}_{D,k}^{MEXO,EX} = \dot{E}_{D,k}^{EX} - \sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{E}_{D,k}^{EX,r} \tag{21}$$

The mexogenous exergy destruction rates for unavoidable-exogenous and avoidable-exogenous exergy destructions are calculated by equations (22) and (23) obtained from [30].

$$\dot{E}_{D,k}^{MEXO,UN-EX} = \dot{E}_{D,k}^{UN-EX} - \sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{E}_{D,k}^{UN-EX,r} \tag{22}$$

$$\dot{E}_{D,k}^{MEXO,AV-EX} = \dot{E}_{D,k}^{AV-EX} - \sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{E}_{D,k}^{AV-EX,r} \tag{23}$$

3. RESULTS AND DISCUSSION

The following considerations and conditions were taken into account for the analyses:

- All processes involved are assumed in steady state.
- Kinetic and potential energies are ignored.
- The decrease in mass flow caused by the accumulation of material on exchanger walls is considered negligible.
- Conditions for the dead state were assumed of 28 °C temperature and a pressure of 101.325 kPa.
- For the unavoidable condition, the design energy efficiency is taken from datasheet.
- Energy Efficiencies for theoretical condition were obtained increasing the unavoidable condition by 20%, higher values cause an excessive elevation in the furnace inlet temperature.

TABLE 1: REAL, UNAVOIDABLE AND THEORETICAL CONDITION FOR EACH HEAT EXCHANGER

HEX	Real η (%)	Unavoidable η (%)	Theoretical η (%)
1-1/3	40,47	56,48	67,78
1-2/4	53,47	60,72	72,87
2-1/2	39,64	59,62	71,54
3-1/3	37,36	57,96	69,55
3-2/4	32,28	54,55	65,46
4	19,17	26,97	32,36
5-1/2	43,07	75,57	90,68
5-3/5	29,23	35,03	42,03
5-4/6	43,99	64,53	77,44
6-1/3	40,59	48,85	58,62
6-2/4	34,76	51,57	61,88
6-5/7	40,42	51,76	62,11
6-6/8	38,30	49,00	58,80

Operating conditions and thermodynamic properties for each state of exchanger network (Fig. 1) are presented in Table 2.

TABLE 2: PROPERTIES FOR EACH STATE OF PREHEAT TRAIN.

State	Substance	$T\ (°C)$	$\dot{m}\ \left(\frac{kg}{s}\right)$	$e\ \left(\frac{kJ}{kg}\right)$	$\dot{E}\ (kW)$
1	CRUDE	155,65	110,02	186,80	20551,74
2	CRUDE	165,85	110,02	207,38	22815,95
3	CRUDE	172,75	110,02	221,76	24398,04
4	CRUDE	187,55	110,02	253,70	27912,07
5	CRUDE	189,55	110,02	258,18	28404,96
6	CRUDE	192,85	110,02	265,64	29225,71
7	CRUDE	192,85	55,01	265,60	14610,66
8	CRUDE	204,45	55,01	292,12	16069,52
9	CRUDE	218,35	55,01	325,11	17884,30
10	CRUDE	227,75	55,01	348,48	19169,88
11	CRUDE	237,85	55,01	374,09	20578,69
12	CRUDE	192,85	55,01	265,69	14615,61
13	CRUDE	198,65	55,01	278,67	15329,64
14	CRUDE	206,45	55,01	296,86	16330,27
15	CRUDE	212,85	55,01	311,92	17158,72
16	CRUDE	225,75	55,01	343,59	18900,89
17	MVGO	242,05	70,03	743,09	52038,59
18	MVGO	229,15	70,03	678,81	47537,06
19	MVGO	218,45	70,03	626,99	43908,11
20	MVGO	197,35	70,03	530,34	37139,71
21	MVGO	182,25	70,03	464,66	32540,14
22	HDIESEL	293,55	35,31	1001,00	35345,31
23	HDIESEL	224,45	35,31	650,25	22960,33
24	AGO	329,55	32,97	1256,09	41413,29
25	AGO	271,85	32,97	918,17	30272,06
26	HVGO	332,05	48,22	1316,03	63458,97
27	HVGO	309,25	48,22	1171,00	56465,62
28	HVGO	287,35	48,22	1040,08	50152,66
29	HVGO	266,85	48,22	922,31	44473,79
30	VR	332,85	33,98	1355,02	46043,58
31	VR	302,75	33,98	1161,09	39453,84
32	VR	279,05	33,98	1017,08	34560,38
33	VR	257,95	33,98	895,82	30439,96
34	VR	241,15	33,98	804,48	27336,23

3.1 Conventional exergetic analysis

The exergy destruction in the preheat train amounts to more than 61 MW, only 18.91 kW of exergy are used from the 80.56 kW provided by hot fluids; consequently, the exergy efficiency of the heat exchanger network is low, with a value of 23.47%. Three heat exchangers present higher exergy destructions rates than the rest, these are the HEX-2-1/2 (two in parallel) and HEX-4, located between the states of the crude line 3-4 and 7-8 respectively (Figure 1). These exchangers are also different from the others because they are the only ones that use products from the atmospheric distillation column to heat the crude oil. The values of the exergy destruction rates and conventional exergy indicators for each exchanger are listed in Table 3.

Percentages of exergy destruction contributed by each heat exchanger are shown in Figure 2. The HEX present relatively similar percentages among them, except three exchangers mentioned above together with HEX-1-2/4 and HEX-6-6/8 for having lower values than the average exergy destruction. Therefore, particularizing and prioritizing the improvement activities in these last four exchangers will not generate significant variations in the performance of the network if considered individually, in contrast to HEX-2-1/2 and HEX-4 whose individual performance does have a great impact on the system's efficiency.

TABLE 3: EXERGY DESTRUCTION, EXEGETIC EFFICIENCY AND EXERGY DESTRUCTION RATIO.

HEX	$\dot{E}_D$ (kW)	ε_k(%)	y_k(%)
1-1/3	5171	33,77	6,42
1-2/4	2353	33,78	2,92
2-1/2	8763	28,66	10,88
3-1/3	3674	18,27	4,56
3-2/4	3152	13,23	3,91
4	9701	13,08	12,04
5-1/2	5546	20,24	6,88
5-3/5	5036	20,26	6,25
5-4/6	3825	32,17	4,75
6-1/3	4863	26,33	6,04
6-2/4	4065	16,93	5,05
6-5/7	3111	24,35	3,86
6-6/8	2392	23,07	2,97
Total	61652	23,47	76,53

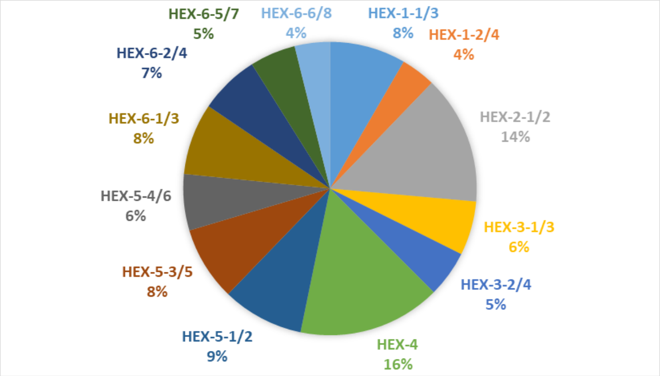

FIGURE 2: EXERGY DESTRUCTION PROVIDED BY HEAT EXCHANGER.

3.2 Advanced exergetic analysis

The results obtained through the analysis of unavoidable and avoidable exergy destruction indicate that only 63% of exergy destroyed can be recovered, which is associated with the formation of fouling inside the heat exchanger.

To establish which heat exchanger is categorized as a key heat exchanger, the avoidable exergy destruction is used not only as a selection parameter, but also as a rule to limit the number of exchangers chosen to 20% of all. Exchangers whose irreversibilities have repercussions on the key heat exchangers will not be considered as critical; they will simply be designated as a source of inefficiency of key heat exchanger under consideration.

The HEX-2-1/2, HEX-4, and HEX-5-1/2 present the highest contributions to avoidable exergy destruction (Figure 3), consequently, those are the exchangers whose improved operating conditions will represent a reduction of 11652.23 kW compared to 38840.76 kW of avoidable exergy destruction of the entire network, hence, these five machines are designated as key heat exchangers.

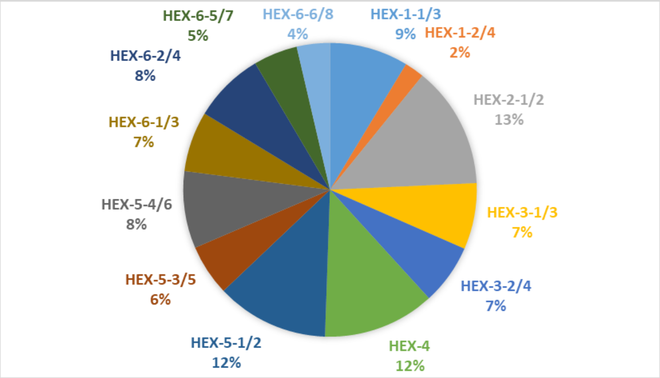

FIGURE 3: CONTRIBUTION TO AVOIDABLE EXERGY DESTRUCTION BY HEAT EXCHANGER

The analysis of the unavoidable and avoidable exergy destruction also indicates which heat exchangers are most affected by fouling. In Figure 4, the greater the difference between the avoidable destroyed exergy compared to unavoidable destroyed exergy, the stronger the impact of fouling on the heat exchanger. Regarding the key heat exchangers, the unavoidable exergy destruction in HEX-2-1/2 and HEX-4 is 3464 kW and 4835 kW respectively, much higher than that generated by HEX-5-1/2 whose value is about 659 kW, then, the impact of fouling in HEX-5-1/2 is so strong as to equate the percentage of avoidable exergy destruction with HEX-2-1/2 and HEX-4 (Figure 4) even though HEX-5-1/2 has a much lower total exergy destruction rate compared to other three key heat exchangers (Table 1).

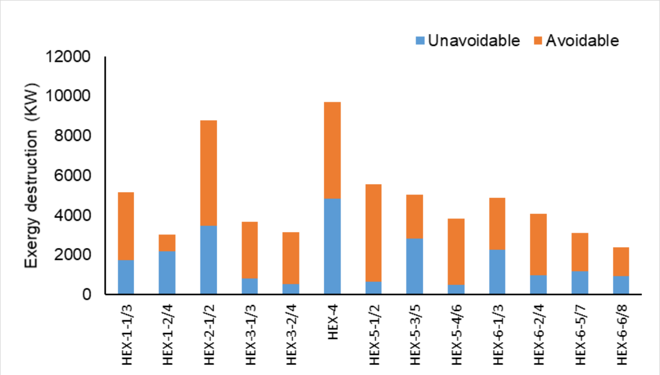

FIGURE 4: DISTRIBUTION OF UNAVOIDABLE AND AVOIDABLE EXERGY DESTRUCTION FOR EACH HEAT EXCHANGER.

The incidence of unavoidable exergy destruction on exchanger performance is determined by comparing e_k and e_k^* (Figure 5), the values of asterisk exergy efficiency are on average nine percentage points higher than e_k. The HEX-1-1/3, HEX-1-

2/4, and HEX-5-3/5 present the most considerable differences, with values of 19.97%, 16.52%, and 16.29% correspondingly, which means that the unavoidable exergy destruction has a significant impact on the efficiency of the exchanger in mention, however, the differences between the two types of exergy efficiency tend to decrease as the heat exchangers are becoming more incrusted, increasing in higher proportion the unavoidable exergy destruction.

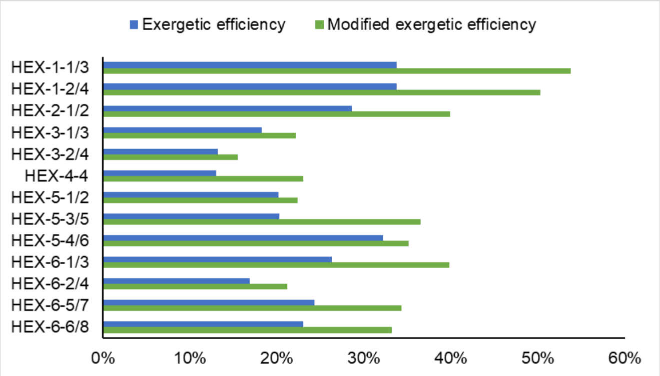

FIGURE 5: CONTRIBUTION TO AVOIDABLE EXERGY DESTRUCTION BY HEAT EXCHANGER

Negative exogenous exergy destructions (Figure 5) indicate that operation at theoretical conditions of remaining equipment significantly improves the performance of the k-component. Only HEX-2-1/2 and HEX-4 show positive exogenous exergy destruction, with a value of 2030 kW and 1236 kW, respectively.

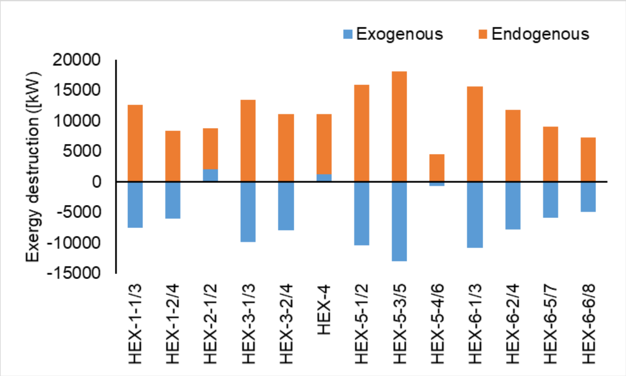

FIGURE 5: DISTRIBUTION OF ENDOGENOUS AND EXOGENOUS EXERGY DESTRUCTION FOR EACH HEAT EXCHANGER.

According to results listed in Table 4, most of the exchangers show a tendency towards endogenous avoidable exergy destruction, then, optimization activities or maintenance works should be focused on equipment under evaluation. HEX-2-1/2 and HEX-4 are the exceptions mentioned above, where the reversible inefficiencies of remaining equipment have a strong impact on the performance of HEX-2-1/2 and HEX-4.

TABLE 4: AVOIDABLE/UNAVOIDABLE ENDOGENOUS AND EXOGENOUS OF EXERGY DESTRUCTION (KW).

HEX	$\dot{E}_{D,k}^{UN,EN}$	$\dot{E}_{D,k}^{AV,EN}$	$\dot{E}_{D,k}^{UN,EX}$	$\dot{E}_{D,k}^{AV,EX}$
1-1/3	2024,00	10601,00	-278,00	-7176,00
1-2/4	2560,25	5824,75	-373,25	-5658,75
2-1/2	3463,68	3269,32	0,32	2029,68
3-1/3	982,11	12503,89	-187,31	-9624,69
3-2/4	2813,71	8275,29	-2285,51	-5651,49
4	6178,33	3630,67	-1343,33	1235,33
5-1/2	979,89	14963,11	-320,39	-10076,61
5-3/5	4078,80	13943,20	-1263,80	-11722,20
5-4/6	2126,18	2336,82	-1650,48	1012,48
6-1/3	2927,32	12703,68	-686,32	-10081,68
6-2/4	1266,77	10556,24	-285,37	-7472,64
6-5/7	1519,72	7484,28	-326,72	-5566,28
6-6/8	1218,72	6033,28	-267,02	-4592,98

Table 5 summarizes the results for mexogenous análisis. Fields with values of zero ("0.00") denote exchangers that have no relationship within the network, positive magnitudes indicate that the irreversibilities of component r contribute to increase the exogenous exergy destruction generated in element k, while negative values denote that the inefficiencies of exchanger r reduce the exogenous exergy destruction in exchanger k. These consequences are the result of changes in thermodynamic properties of flows due to variations in the temperatures of crude oil and heat transferring fluids.

HEX-1-1/3 and HEX-1-2/4 contribute 49% and 11% to exogenous exergy destruction in HEX-2-1/2 and in HEX-4 the largest contributions to exogenous exergy destruction come from HEX-3-1/3 and HEX-3-2/4 with 35% and 31%, respectively.

In general, the irreversibilities of exchangers usually have repercussions on predecessor elements, but their incidence depends on the number of intermediate machines operating under optimal conditions, as the greater the number of machines, the lower repercussion on exergy destruction, since the intermediate exchangers will assume the effects (in small proportions each) of irreversibilities of the r-component. Additionally, the results obtained in the divisions of mexogenous analysis (Table 6 and Table 7) indicate that the interactions related to unavoidable exogenous exergy destruction dominate the effects of remaining irreversibilities, which indicates that it is possible to carry out improvement works (cleaning) in the exchangers that harm key heat exchangers.

The interdependencies between the components and mexogenous exergy destruction related to avoidable-exogenous exergy destruction are shown in Table 7 where it is possible to quantify the effect of reversible inefficiencies coming from each component, in synthesis, it is only convenient to implement the strategy of "indirect improvement works" in heat exchangers that have influence on HEX-2-1/2 and HEX-4 since in other components the individual effects can be considered insignificant (on average 73 kW).

It is necessary to clarify that although the idea of increasing irreversibilities in the elements whose malfunctioning benefits the reduction in exergy destruction in some exchangers could be considered, this strategy would also affect the predecessor equipment of component to which irreversibilities are added, consequently causing an increase negative effects in downstream exchangers.

TABLE 5: ENDOGENOUS EXERGY OF COMPONENT K AND THE EXOGENOUS PART CAUSED BY COMPONENT R (MW).

r		HEX												
k		**1-1/3**	**1-2/4**	**2-1/2**	**3-1/3**	**3-2/4**	**4**	**5-1/2**	**5-3/5**	**5-4/6**	**6-1/3**	**6-2/4**	**6-5/7**	**6-6/8**
HEX	**1-1/3**	12,63	0,60	0,00	-1,08	-2,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	1-2/4	-2,17	8,39	0,00	-1,01	-2,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	2-1/2	1,00	0,22	6,73	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	3-1/3	0,40	0,01	0,69	13,49	-5,08	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	3-2/4	0,05	0,01	0,27	-3,89	11,09	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	4	0,08	0,02	0,26	0,38	0,43	9,81	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	5-1/2	0,11	0,01	0,16	0,10	0,03	0,13	15,94	0,57	-8,10	0,00	0,00	0,00	0,00
	5-3/5	0,02	0,01	0,29	0,10	0,05	0,06	-4,41	18,02	0,31	0,00	0,00	0,00	0,00
	5-4/6	0,02	0,03	0,02	0,04	0,04	0,22	-0,45	-0,30	4,46	0,00	0,00	0,00	0,00
	6-1/3	0,08	0,02	0,11	0,27	0,03	0,00	0,00	0,00	0,00	15,63	-11,17	0,26	0,18
	6-2/4	0,01	0,04	0,07	0,08	0,01	0,00	0,00	0,00	0,00	-4,17	11,82	0,11	0,37
	6-5/7	0,02	0,03	0,04	0,04	0,02	0,00	0,00	0,00	0,00	-1,07	-1,69	9,00	0,90
	6-6/8	0,05	0,12	0,59	0,29	0,11	0,00	0,00	0,00	0,00	-1,78	-2,21	-1,59	7,25

TABLE 6: UNAVOIDABLE ENDOGENOUS EXERGY OF COMPONENT K AND THE UNAVOIDABLE EXOGENOUS PART CAUSED BY COMPONENT R (MW).

r		HEX												
k		**1-1/3**	**1-2/4**	**2-1/2**	**3-1/3**	**3-2/4**	**4**	**5-1/2**	**5-3/5**	**5-4/6**	**6-1/3**	**6-2/4**	**6-5/7**	**6-6/8**
HEX	**1-1/3**	2,02	0,14	0,00	-0,30	-0,32	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	1-2/4	-0,65	2,56	0,00	-0,25	-0,40	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	2-1/2	0,28	0,05	3,46	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	3-1/3	0,07	0,00	0,21	0,98	-1,17	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	3-2/4	0,01	0,00	0,09	-0,70	2,81	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	4	0,02	0,00	0,06	0,12	0,10	6,18	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	5-1/2	0,02	0,00	0,05	0,03	0,01	0,03	0,98	0,11	-1,62	0,00	0,00	0,00	0,00
	5-3/5	0,01	0,00	0,10	0,02	0,02	0,01	-1,41	4,08	0,06	0,00	0,00	0,00	0,00
	5-4/6	0,00	0,01	0,00	0,01	0,02	0,04	-0,07	-0,06	2,13	0,00	0,00	0,00	0,00
	6-1/3	0,03	0,00	0,03	0,06	0,01	0,00	0,00	0,00	0,00	2,93	-2,68	0,06	0,06
	6-2/4	0,00	0,01	0,02	0,02	0,00	0,00	0,00	0,00	0,00	-1,17	1,27	0,02	0,12
	6-5/7	0,01	0,01	0,01	0,01	0,01	0,00	0,00	0,00	0,00	-0,34	-0,53	1,52	0,32
	6-6/8	0,02	0,02	0,10	0,05	0,02	0,00	0,00	0,00	0,00	-0,36	-0,71	-0,25	1,22

TABLE 7: AVOIDABLE ENDOGENOUS EXERGY OF COMPONENT K AND THE AVOIDABLE EXOGENOUS PART CAUSED BY COMPONENT R (MW).

	k \ r	**HEX**												
		1-1/3	**1-2/4**	**2-1/2**	**3-1/3**	**3-2/4**	**4**	**5-1/2**	**5-3/5**	**5-4/6**	**6-1/3**	**6-2/4**	**6-5/7**	**6-6/8**
HEX	**1-1/3**	10,60	0,46	0,00	-0,78	-1,68	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	1-2/4	-1,52	5,82	0,00	-0,76	-1,70	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	2-1/2	0,72	0,17	3,27	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	3-1/3	0,32	0,01	0,47	12,50	-3,91	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	3-2/4	0,04	0,01	0,18	-3,19	8,28	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	4	0,07	0,01	0,20	0,26	0,34	3,63	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	5-1/2	0,09	0,01	0,11	0,07	0,02	0,10	14,96	0,45	-6,48	0,00	0,00	0,00	0,00
	5-3/5	0,01	0,01	0,19	0,08	0,04	0,05	-3,00	13,94	0,26	0,00	0,00	0,00	0,00
	5-4/6	0,01	0,02	0,02	0,03	0,03	0,18	-0,38	-0,24	2,34	0,00	0,00	0,00	0,00
	6-1/3	0,06	0,01	0,08	0,22	0,03	0,00	0,00	0,00	0,00	12,70	-8,49	0,21	0,12
	6-2/4	0,01	0,03	0,05	0,06	0,01	0,00	0,00	0,00	0,00	-3,00	10,56	0,09	0,25
	6-5/7	0,01	0,02	0,03	0,02	0,01	0,00	0,00	0,00	0,00	-0,73	-1,17	7,48	0,59
	6-6/8	0,03	0,10	0,50	0,24	0,09	0,00	0,00	0,00	0,00	-1,43	-1,50	-1,34	6,03

4. CONCLUSION

This investigation takes as a case study the preheat train of a crude oil distillation unit, conventional and advanced exergy analyses are used to estimate the improvement potential of the system and the critical spots. The results of this study conclude the following:

- The highest exergy destruction rates come from five heat exchangers, which are considered priority equipment to be intervened due to their impact on the network.
- Conducting efforts to eliminate avoidable irreversibilities in all exchangers of preheat traing result in a reduction of approximately 38.49 MW in exergy destruction, which in turn will mean a higher inlet temperature at furnace and thus a reduction in fuel consumption and environmental impacts.
- Using mexogenous analysis and its subdivisions, it is possible to establish improvement works indirectly, in case it is not possible to execute maintenance activities on the equipment under consideration.
- To heat exchangers that are not considered key heat exchangers, improvement activities involving several of them should be established, since by themselves these components do not represent major changes in the performance of the network, but together they will generate more than 27.18 MW of exergy destruction that could be recovered.

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NOMENCLATURE

T	Temperature (°C)
$\dot{m}$	Mass flow $\left(\frac{kg}{s}\right)$
C_P	Heat Capacity $\left(\frac{kJ}{Kg\,°C}\right)$
SG	Specific gravity $(-)$
k_w	Watson factor $(-)$
h	Specific enthalpy $\left(\frac{kJ}{Kg}\right)$
s	Specific entropy $\left(\frac{kJ}{Kg\,K}\right)$
e	Specific exergy $\left(\frac{kJ}{kg}\right)$
$\dot{E}$	Exergy (kW)
Abreviations	
CDU	Crude oil destillation unit
PHT	Preheat train
HEX	Heat exchanger
HEN	Heat exchanger network
BPD	Barrels per day
HVGO	Heavy vacuum gas oil
MVGO	Medium vacuum gas oil
AGO	Atmospheric gas oil
HDIESEL	Heavy diesel
VR	Vacuum residue
Greek letters	
η	Energy efficiency
ε	Exergy efficiency
y	Exergy destruction ratio
Subscripts	
0	Dead state
*	Modified
i	i-th flow

k	k component
R	r component
Avg	Average
D	Destruction
P	Product
F	Fuel
PT	Potential
KN	Kinetic
PH	Physic
CH	Chemical
AV	Avoidable
UN	Unavoidable
EN	Endogenous
EX	Exogenous
MEXO	Mexogenous

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