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APPLICATION OF THE CONCEPTS OF EXERGY AND PROCESSES INTEGRATION IN THE PRE-HEATING SYSTEM IN DISTILLATION UNIT IN A PETROLEUM REFINERY

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Abstract: *The oil refining process is the chemical industry that has higher energy consumption. Currently, 6% of the total oil processed is consumed within the refinery; that percentage should increase due the use of more units of conversion. Reviews have shown that there is a rate of energy that can be recovered, which is the result of the balance among, the energy consumed under actual plant conditions and the amount of minimum energy required to carry out a process in real conditions. The objective this paper is mainly directed to the analysis of the pre-heating system in the atmospheric distillation unit, which has a great potential for recycle of energy. Due to several configurations for pre-heating systems, it is are assumed three heat exchangers hypothetical models in the study. To accomplish the design it is necessary to select the products of the atmospheric distillation tower that possess high temperatures, whose energy can be used in the pre-heating process. The exergy analysis was developed with the application of the second law of thermodynamics for calculating the lost energy in the three models assumed for the pre-heating process of the crude oil; verify that the pre-heating system has direct influence on the energy consumptions of the atmospheric distillation unit.*

Keywords: *Exergy, Processes Integration, Pre-heating, Refinery*.

1. INTRODUCTION

The oil refining process is a series of operations that separate the crude oil in various fractions, generating, a variety of derivatives as liquefied petroleum gas (LPG), gasoline, diesel oil, among others, which serve as inputs for various industries or even as finished products. (Pinto, 2004)

The oil refining process is responsible, approximately, by 52% throughout fuel consumption. Currently, 6% of the total oil processed is consumed within the refinery; that percentage should increase due the use of more units of conversion. DOE (1998) developed studies and reviewed several oil refining industries, and demonstrated a amount of energy that may be recovered (*Energy Bandwidth*) that is the difference between the energy consumed by the process under actual plant conditions, *Current Average Energy* (*CAE*), and the amount of minimum energy required to carry out a process in real conditions *Practical Minimum Energy* (*PME*). From the study it was verified that the unit of atmospheric distillation has the annual percentile largest of recoverable energy in comparison with the other units of the refining process. (Table 1)

The basic approach of the study is driven to the analysis of the pre-heating system in the atmospheric distillation. This step, which is one of the most significant and of interest, has great potential for reuse of energy. This pre-heating system is proposed to heat the flow of crude oil gradually before entering to the tower of atmospheric distillation. The correct operation of the pre-heating system influences directly in the consumption of fuel of the furnace and in the performance of the distillation stage. (DOE, 1998)

Table 1. The TME, PME, and CAE and Energy Bandwidth values for the five principal oil refining processes

Process	TME*	PME*	CAE*	Energy Bandwidth (CAE - PME)	Potential Energy Bandwidth	Total Annual CAE by Process (10^{12} kJ/yr)	Potential Energy Bandwidth Savings (10^{12} kJ/yr)
1.Crude Distillation:							
Atmospheric	146	333	727	394	54%	693	375
Vacuum	307	360	594	234	39%	255	100
2. Fluid Catalytic Hydrotreating	267	880	1220	340	28%	397	110
3.Catalytic Hydrotreating	200	367	540	173	32%	402	130
4.Catalytic Reforming	527	1354	1761	407	23%	357	82
5. Alkylation							
H_2SO_4	-387	1040	1667	627	38%	107	40
HF	-387	1013	1634	621	38%		

(*) kJoule/ m^3. Source: DOE (2006)

2. DISTILLATION ATMOSPHERIC

A very important unit in the oil refining process is the distillation, which is a primordial stage of the refining process. The crude oil after being received and stored pass by a desalter process, and after this the temperature of the crude oil is in the interval of 150 and 170ºC. Among the distillation and desalter stage, it is necessary a process of pre-heating which has for purpose to gradually increase the temperature of crude oil flow, before entering to the atmospheric distillation tower; this process is accomplished by one heat exchangers set continuously of a furnace. The heat exchangers set has as function pre-heat the crude oil after the desalter process until a temperature interval among 270 and 280ºC, in order that finally it is heating in a furnace until the temperature of 400ºC for later to be injected in the atmospheric distillation tower.

The distillation is a process in which the crude oil is loaded in the distillation tower to a temperature of approximately 400ºC, and is heated with a overheated steam flow to maintain a constant temperature. This cause the physical separation of the most volatile fractions of crude oil. The “Figure 1” presents the atmospheric distillation unit, composed of several compartments, which are known as plates or as trays distributed in the unit. Each tray is responsible for collection of products. When the tower bottom-up identifies that the products are less a volatile condense at the bottom of the tower, and require higher temperatures for its evaporation, the boiling point are very higher. The more volatile fractions that have lower boiling points of condensed will be at the top of the tower, where temperatures are lower, therefore requiring higher temperatures for its evaporation, (Mariano, J.B. 2001).

A distillation tower operating at atmospheric conditions has products such as diesel oil, kerosene and heavy naphtha. The heavier fractions that cannot be vaporized in the tower are drawn in the bottom of column in the form of asphalt or heavy oil and other heavy products. Later these products will be vaporized in the vacuum distillation tower, because such waste can still be withdrawn important fractions. Another product generated in the atmospheric distillation is the gas refinery, composed mainly of methane and ethane. Normally this gas contains hydrogen sulfide and ammonia fumes. This gas is sent to a treatment system, and purified, it is used as fuel for heating furnaces. The products leaving the tower distillation of most interest to this work are those with sufficiently high temperatures, whose energy can be used in the actual process of distillation, generating energy saving, (Gary, 2001). “Table 2” shows physical properties of the fractions of crude oil.

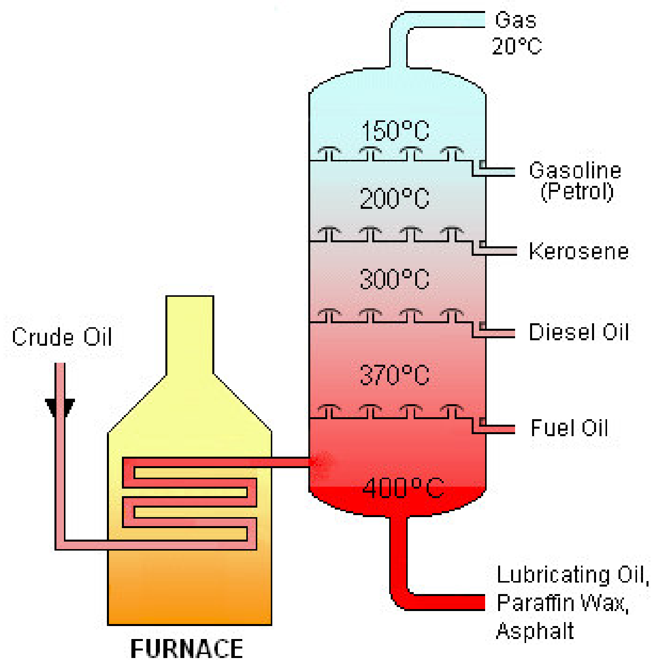

Figure 1. Atmospheric distillation tower.

Table 2. Crude oil fractions.

Product	Volume (%)	Density (kg/m^3)	Cp (kJ/kg K)	Boiling point (°C)
Gas	1.2	539.21	2.2970	20
Gasoline	4.3	677.25	2.2635	150
Kerosene	4.3	515.25	2.1966	200
Diesel oil	10.8	820.00	2.2049	300
Fuel oil	24.7	862.23	2.0900	370
Atmospheric bottoms	54.1	968.06	2.0961	400

Source: DOE (2006)

3. PRE-HEATING SYSTEM ANALYSIS

The distillation tower heat exchangers set has as primary function, to pre-heat the crude oil with the hot products from the distillation tower. The thermal energy of the products are exploited in a number of shell and tube heat exchangers; this exchangers consist of a series of tubes, one set of these tubes contains the fluid that must be either heated or cooled. (Pinto, 2004)

Due to the variety of configurations for pre-heating systems, it is are assumed three heat exchangers hypothetical models of parallel currents considering a average efficiency of 80%, (Cornelissen 1999).

To accomplish the design it is necessary to select the products of the distillation tower that possess high temperatures, whose energy can be used in the pre-heating process. It is also considered the flows with a mass flow rate and high specific heat capacity that can be used as the heating currents of the pre-heating system. Taking into account these considerations, diesel oil, fuel oil and the atmospheric bottoms are selected and their characteristics are shown in the Tab. 3.

Table 3. Products of atmospheric distillation selected for the study.

Product	Mass flow rate (kg/h)	Cp (kJ/kg °C)
Diesel oil	576	2.2049
Fuel oil	1584	2.0900
Atmospheric bottoms	3456	2.0961

Source: DOE (2006)

For this analysis it has been considered a crude oil volumetric flow rate of approximately 1000 barrels of crude oil per day, (DOE 2006). The properties of crude oil used in the study are presented in Tab. 4.

Table 4. Physical properties crude oil.

Product	Density (1) (kg/ m^3)	Cp (2) (kJ/kg °C)	Volumetric Flow Rate (2) (m^3/h)	Mass Flow Rate (2) (kg/h)
Crude oil	852	2.719	6.624	5643.648

Fonte: (1) Mott, R. (1996); (2): DOE (1998)

In the analysis of the pre-heating system, concepts of energy and exergy were applied with the purpose of diagnosing the level of energy performance of the hypothetical model to quantify the entries and exits of heat. Steady state conditions were considered the control volume balance, (Freitas, 1995; Moran, M. J.; Shapiro 2002).

Conservation of the mass

$$\sum_i \dot{m}_{in} = \sum_o \dot{m}_{out} \tag{1}$$

Conservation of energy

$$\sum_i \dot{E}_{in} = \sum_o \dot{E}_{out} \tag{2}$$

Exergy destroyed

$$\sum_i \dot{E}x_{in} - \sum_o \dot{E}x_{out} = \sum \dot{E}x_{dest} \tag{3}$$

Exergy balance equation under the form of the rate steady state:

$$0 = \sum_i \left(1 - \frac{T_0}{T_i}\right)\dot{Q}_i - \dot{W}_{vc} + \dot{m}(e_{f1} - e_{f2}) + \dot{m}(e_{f3} - e_{f4}) - Ex_{dest} \tag{4}$$

Physical exergy for a control volume

$$e_{f1} - e_{f2} = (h_1 - h_2) - T_0(s_1 - s_2) \tag{5}$$

Exergy destroyed of the equation 4

$$Ex_{dest} = \dot{m} \cdot (e_{f1} - e_{f2}) + \dot{m} \cdot (e_{f3} - e_{f4}) \tag{6}$$

Second law efficiency or exergetic efficiency

$$\varepsilon = \frac{\dot{m}_{cold} \cdot (e_{f4} - e_{f3})}{\dot{m}_{heat} \cdot (e_{f1} - e_{f2})} \tag{7}$$

4. DISCUSSION AND RESULTS

"Table 5" shown the classification of cold and hot flows with the corresponding inlet and outlet temperatures designated for the first model as an initial stage. The "Figures 2, 3, 4" represent the three heat exchangers hypothetical models with the respective temperatures. For the design of the heat exchangers systems, a gradient of heat in the range 10 to 20 °C were assumed between hot and cold flows for assuring the thermal exchanges.

It is also considered an thermal efficiency of 80 % for each heat exchangers mentioned in item 3, (Linnholff and Turner, 1981). With this estimation it is possible to formulate approximate configurations for the heat exchangers hypothetical models. These temperatures vary according to the heat exchangers distribution in the different pre-heating models.

Table 5. Classification of the flows.

Number	Classification	Streams	Inlet temp. (°C)	Outlet temp. (°C)	CP*	Thermal Load (kJ/h)
1	Hot	Diesel oil	320	170	1293.44	194016.24
2	Hot	Fuel oil	370	230	3310.56	463478.40
3	Hot	Atmospheric bottoms	400	250	7244.12	10866618.24
4	Cold	Crude oil	150	240	15958.61	159586.13

(*) Heat capacity flow rate in kJ/h °C

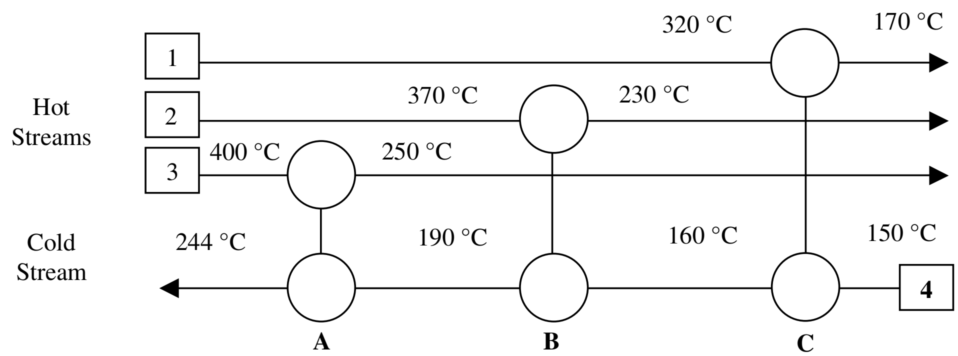

Figure 2. First heat exchangers model.

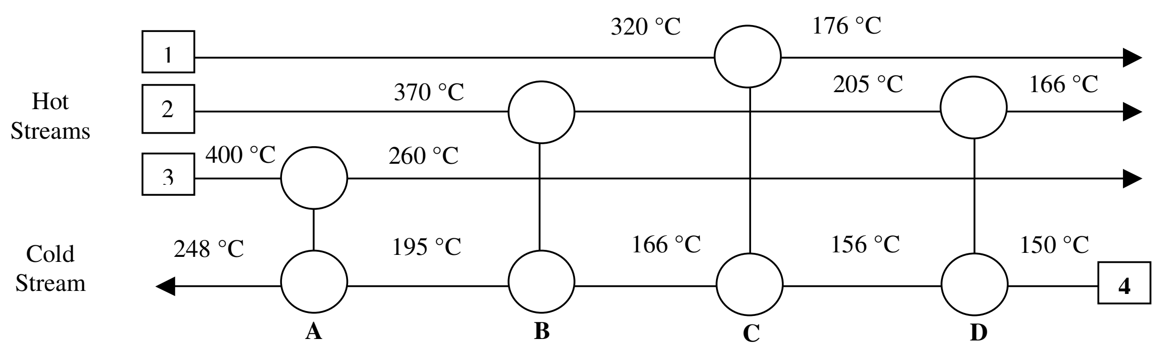

Figure 3. Second heat exchangers model.

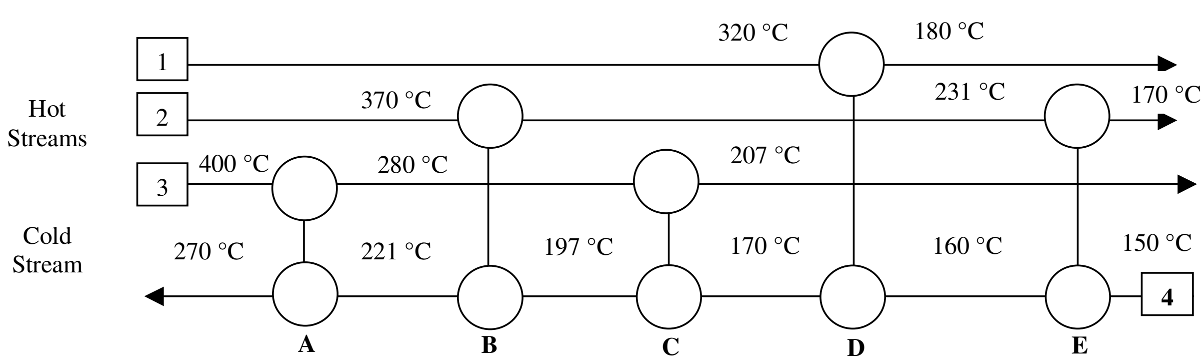

Figure 4. Third heat exchangers model.

"Table 6" shows the final results for the three heat exchangers hypothetical models. The results highlights that the decrease of the destroyed exergy and the increase the exergy efficiency is compatible with the number of heat exchangers in each model and the correct integration of streams. In "Figure 5" it can be observed the increase of outlet temperature of crude oil in the three heat exchangers models assumed in the study. The first heat exchangers model can heat the crude oil until the value of 244°C, but in this configuration it can may be observed that the outlet temperature of hot currents still have a quantity of energy that is not used. The second heat exchangers model present a modification, this add one heat exchanger in the current 2 with the aim to recover a proportion of lost energy. This modification allows the increase in the temperature of crude oil until 248°C. The third heat exchangers model incorporate a heat exchanger additional in the current 3. This modification allows recovering a proportion of energy achieving crude oil a temperature of 270°C required in the pre-heating process.

Table 6. Total results.

Heat exchanger	Thermal Efficiency (1)	Exergy Efficiency (1)	Exergy Destroyed (kWatts) (1)	Thermal Efficiency (2)	Exergy Efficiency (2)	Exergy Destroyed (kWatts) (2)	Thermal Efficiency (3)	Exergy Efficiency (3)	Exergy Destroyed (kWatts) (3)
A	0.80	0.75	63.01	0.80	0.77	60.96	0.86	0.84	36.67
B	0.80	0.75	35.18	0.80	0.76	33.70	0.80	0.77	26.94
C	0.80	0.77	11.84	0.80	0.75	11.88	0.80	0.77	30.13
D	-	-	-	0.80	0.77	6.84	0.80	0.76	10.80
E	-	-	-	-	-	-	0.80	0.77	11.36
Mean	0.80	0.76	36.68	0.80	0.76	28.17	0.81	0.78	23.18

(1): First heat exchangers model; (2): Second heat exchangers model; (3): Third heat exchangers model.

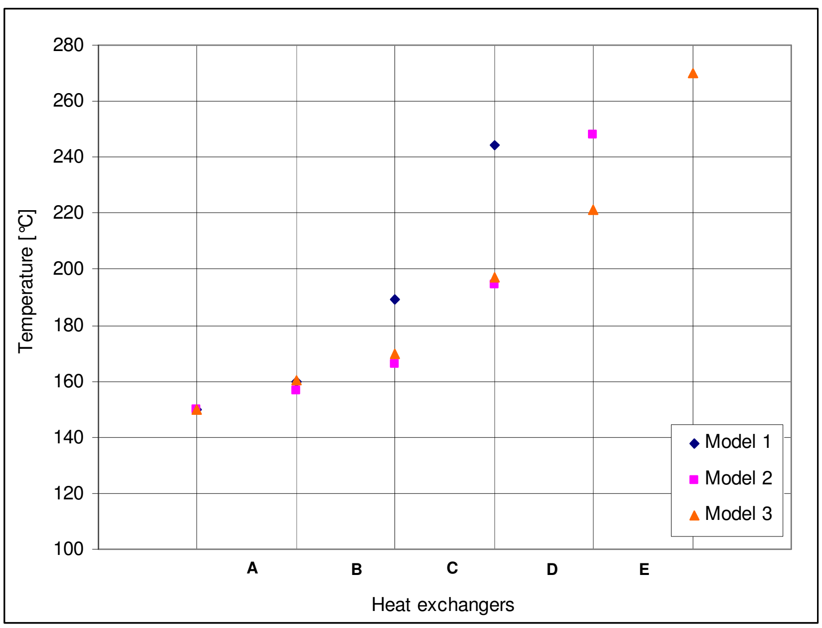

Figure 5. Outlet temperature of crude oil in the three heat exchangers models assumed in the study.

5. CONCLUSION

The distillation atmospheric tower heat exchangers set are an example of the process integration, because it is recovers a great quantity of thermal energy of the hot products by means of a correct configuration of exchangers. The exergy analysis was developed with the application of the second law of thermodynamics for calculating the lost energy in the three models assumed for the pre-heating process of the crude oil.

The aim of this exergetic analysis was to develop an analysis of the exergy destroyed to propose a more efficient process. The results shows that the third heat exchangers hypothetical model achieves the minimum required temperature for the pre-heating process, because this third model has a great number of heat exchangers, specifically between hot products flows.

It was also verified that the pre-heating system has direct influence on the energy consumptions of the atmospheric distillation unit.

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