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Computer-Aided Exergy Analysis of Colombian Crude Oil Production and Refining

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Abstract

Exergy analysis can be used in design, simulation, comprehensive evaluation and improvement of technological processes due to it measures quantity and quality of matter and energy flows of each stage of production process. In this work, exergy analysis of production and refining of 1,000 barrels per day of a Colombian crude oil with 29 °API was evaluated using a commercial process simulation software, in which a full battery production and atmospheric distillation unit were simulated. Results showed that battery production presented a very high exergetic efficiency with a value of 97 %, but the atmospheric distillation unit has an exergetic efficiency of 47 %, which indicates the need for energy and mass process integration to reduce the amount of industrial services.

Keywords: CAPE, Simulation, Colombian crude oil, exergy analysis

1. Introduction

For foreseeable future, crude oil are expected to continue dominating global demands of energy sources, nevertheless, it is not attended by the enough availability of non-renewable oil, so depletion of conventional crude oil reserves has led to face challenges in its production and refining such as enhanced recovery, production in unconventional oil deposits and heavy crudes refining [1, 2]. Even, improved oil recovery techniques have become more cost-effective due to increasing oil prices and advances in technology [3]. Crude oil is a crucial strategic resource with significant impacts on economic development, growth for industrialized and financial markets [4, 5]. Colombia is the third-largest oil producer in South America after Venezuela and Brazil, thus its economy is highly dependent of this energy commodity and requires improving oil production and refining processes to ensure profitability [6].

Computer-aided software-tools complemented by methodologies (e.g. exergy analysis) are considered useful alternatives for generation, evaluation and determination of more sustainable processes and its improvements [7]. Exergy analysis compensates loss due to irreversibility of the system and allows measuring the quantity and quality of energy sources [8]. Also, it is a useful method to establish strategies to design and operate many industrial processes and to analyze its sustainability from energetic point of view [9]. This methodology quantifies the quality of heat in a waste stream, indicates the locations of energy degradation into the process, causes and true magnitudes of exergy losses and identifies meaningful efficiencies, therefore can lead to improve technology operation [10]. This paper presents the simulation and exergetic evaluation of battery production and refining of a Colombian crude oil using a commercial process simulation software, based on API gravity of mixture, thus serving to any similar crude.

2. Materials and Methods

Computer-aided simulation

For computer-aided simulation, a commercial process simulation software was used. Battery of production was simulated to clean crude oil coming from wells, in order to reduce water, salts and sediments content. This part of simulation was performed using three hypothetical wells which characteristics belong to Caño Limón crude that has a density of 29 °API. Two of the wells were simulated with a flow of 45,000 bpd (barrels per day) and the other one with 1,000 bpd. The Assay found in the software database was applied for the crude oil characterization. Peng-Robinson model was used as thermodynamic package, because of it is recommended for oil, gas and petrochemicals applications. Unknown properties were estimated using UNIFAC (Universal Functional Group Activity Coefficient) model and the database Thermo Data Engine (TDE). After entering the crude oil components, it was settled in the stream function as oil-rich stream (crude 1, crude 2 and crude 3).

Exergy analysis

Energy and exergy balances for the processes were calculated as follows. The flow in a system for a finite time interval can be described according to Equation 1:

$$\textit{Exergy input-exergy output-exergy consumption} = \textit{Exergy accumulation} \quad (1)$$

Therefore, global exergy balance is given by Equation 2.

$$\dot{E}x_{mass,in}-\dot{E}x_{mass,out}+\dot{E}x_{heat}-\dot{E}x_{work}=\dot{E}x_{loss} \quad (2)$$

The mass exergy component shown in Equation 3, is divided into four specific components: the physical exergy ($\dot{E}x_{phy}$) related to temperature, enthalpy and entropy given by Equation 4; chemical exergy ($\dot{E}x_{chem}$) related to the chemical exergy of each compound per mol ($Ex^0{}_{ch}$); potential exergy ($\dot{E}x_{pot}$) and kinetic exergy ($\dot{E}x_{kin}$). The calculation of chemical exergy of each compound per mol ($Ex^0{}_{ch}$) is given by Equation 5. This is a function of the chemical exergy of each elemental compound ($Ex^0{}_{ch,i}$), number of atoms of each element contained into the stream (n_{elem}) and Gibbs free energy of formation for the compound (ΔG_f^0).

$$\dot{E}x_{mass}=\dot{E}x_{phy}+\dot{E}x_{chem}+\dot{E}x_{pot}+\dot{E}x_{kin} \quad (3)$$

The physics exergy related with temperature, entropy and enthalpy:

$$\dot{E}x_{phy}=\left(\dot{H}-\dot{H}_0\right)-T_0\left(\dot{S}-\dot{S}_0\right) \quad (4)$$

Where H is the enthalpy, S is the entropy, T_0 is the environmental temperature or in dead state, H_0, and S_0 are enthalpy and entropy in dead state, respectively.

$$Ex^0{}_{ch}=\Delta G_f^0+\Sigma_i n_{elem}\times Ex^0{}_{ch,i} \quad (5)$$

The chemical exergy of the process streams was evaluated by Equation 6, where y_i is the molar fraction of component i, $Ex^0{}_{ch,i}$ is chemical exergy of pure compound, T_0 is reference temperature and R is the gas constant. Kinetic and potential exergy was neglected because of its contribution to the total exergy balance is minimal.

$$Ex_{ch,stream}=\sum_i y_i\times Ex^0{}_{ch,i}+RT_0\sum_I y_i\times ln(Y_I) \quad (6)$$

To calculate process lost exergy and process efficiency, the following equations were used. $\dot{E}x_{in,\ total}$ refers to the total exergy for the inlet main stream, $\dot{E}x_{u,\ total}$ is total exergy of utilities, $\dot{E}x_{out,\ total}$ is the total exergy for the outlet main stream [11].

$$\dot{E}x_{lost}=\dot{E}x_{in,\ total}+\dot{E}x_{u,\ total}-\dot{E}_{out,\ total} \quad (7)$$

$$Process\ efficiency=\left[1-\left(\frac{\dot{E}x_{lost}}{\dot{E}x_{in,\ total}+\dot{E}x_{u,\ total}}\right)\right]*100 \quad (8)$$

3. Results and Discussion

Simulation of oil production battery

To simulate oil production battery, two separator were used for water and oil, one general and the other for testing. All gases leaving the separator (test and general) arrive to torch drum, where traces of oil are removed to be finally burned in the torch. The liquid part that leaves general separator goes to the Gun Barrel, which is a washer tank operated at atmospheric pressure, it is used to remove any percentage of water and gas still present in on-going oil to refinery. Water is separated using difference in density between water and oil, thus, oil overflows and water remains in the Gun Barrel. The general separator receives crude from wells 1 and 2, the gas is send to the torch drum and the liquid part towards Gun Barrel. Figure 1 shows computer-aided simulation of the production battery.

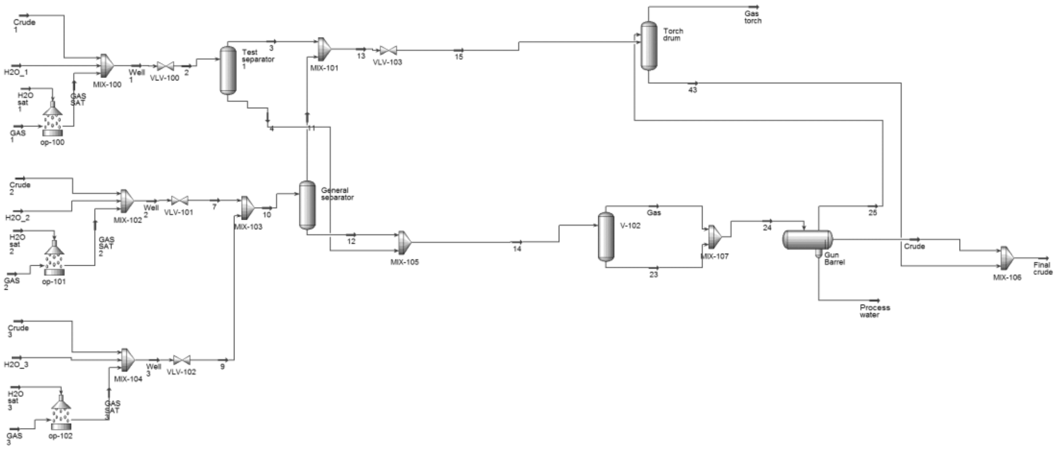

Figure 1. Simulation of the production battery

Simulation of oil refining process

Refining process separates useful components from crude oil. This separation is achieved by many physicochemical processes, but this research is focused just on atmospheric distillation. The crude oil is pumped at a rate of 1,000 bpd and 77 °F to the refinery, heading towards a heat exchanger to raise its temperature, then it enters to a three-phase separator, which acts as a desalter with the aim of withdrawing all organic salts that oil and water may have. After that, crude is conduced to a train of heat exchangers to reach the furnace temperature required for sending it to the distillation column. In this column are separated refined gasoline, kerosene, diesel and finally fuel oil, to be processed separately. As it is shown in Figure 2, refined gasoline flows through an air cooler where temperature and pressure are reduced, then it heads towards to a three-phase separator that acts as a top accumulator, where gas, refined gasoline and wastewater are separated. The gas is sent to a separator that withdraw any residue still present on it and the rest is burned at the torch; refined gasoline is pumped and split into two streams, one ready to continue in the process and other that returns to the tower through refluxes; and wastewater leaves for later treatments. Kerosene flows to a stripper kero-tower that uses an inlet steam to remove pollutants, this in order to get proper quality of kerosene to use in subsequent stages and to return a part to the tower as reflux. Diesel is divided in two streams, one is pumped as utility to heat crude that enter to distillation tower, and the other is sent to a diesel stripper that works as the kerostripper, where a part of diesel is used as reflux and the other one for later stages. Finally, fuel oil is conduced to a separator where it is washed with water, then is separated in two streams, one that returns to the tower as reflux and other sets aside for subsequent stages. Steam streams used in stripper towers are given by a stream of water heated in a boiler, leaving a purge stream.

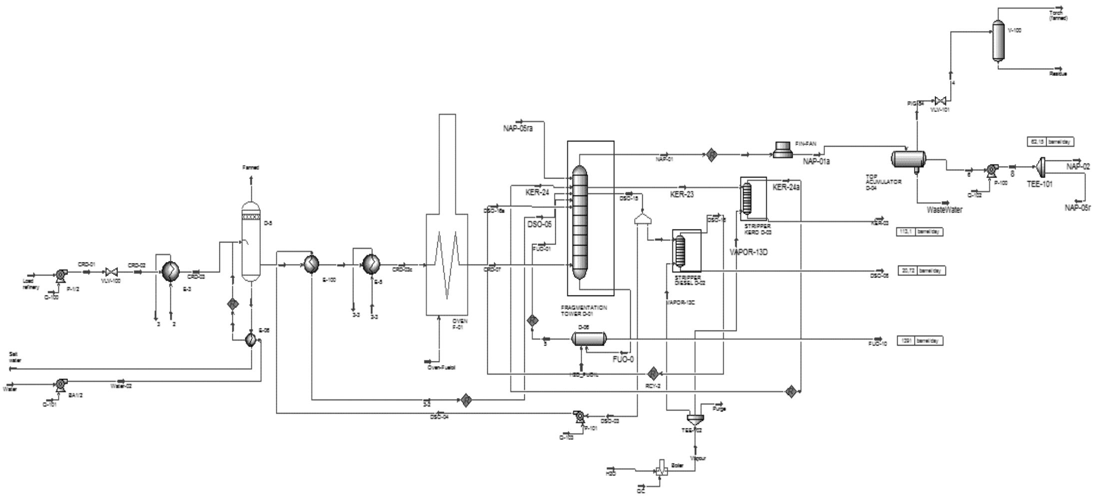

Figure 2. Computer-aided Simulation of crude oil refining process.

Exergy analysis of the process

Physical, chemical and total exergy of main input and output streams in battery production and refining of crude oil are shown in Table 1 and Table 2, respectively.

Table 1. Physical, chemical and total exergy of main streams in battery production process

	Stream	**Physical Exergy (Btu/h)**	**Chemical Exergy (Btu/h)**	**Total exergy (Btu/h)**
Inlet streams	Well 1	198,156	3,008,830	3,206,986
	Well 2	446,995	9,647,499	10,094,495
	Well 3	446,995	9,647,499	10,094,495
	Total			23,395,975
Outlet stream	Final crude	732,845	22,102,003	22,834,849
Residues	Gas torch	98,453	201,765	300,218
	Process water	260,848	59.92	260,908
	Total			561,126

Table 2. Physical, chemical and total exergy of main streams in refining of crude oil process

	Stream	Physical Exergy (Btu/hr)	Chemical Exergy (Btu/hr)	Total exergy (Btu/hr)
Inlet streams	Load refinery	0.06	931,959,345	931,960,607
	Water	0.08	3.13	219.17
	H_2O	62.92	11.93	629,256
	H_2O_FUOIL	60.76	0.012	607.66
	Total			932,590,690
Outlet streams	NAP-02	3.57	10,277,712	10,280,032
	KER-03	51.79	269,893,134	269,958,290
	DSO-08	68.45	26,20,944	2,637,237
	FUO-10	117.67	181,538,888	183,689,172
	Total			466,564,731
Residues	Salt water	0.63	3.13	1,648
	Purge	362.92	11.92	3,625,998
	Torch (fanned)	31.58	195,995	198,848
	Residue	3.97	145,057	145,098
	Total			3,971,591
Utilities	2	154,92,816	11,339,120	26,831,936
	Water-04 salt	34,761	593,566	628,327
	2-3	16,543,032	11,339,120	27,882,152
	DSO-04	225,931	28,969,124	29,195,055
	Q-101			1,847
	Q-100			18,641
	Q-103			102.33
	Q-102			168.12
	Oven fuel oil			4,946,609
	Qc			8,666,470
	Total			98,171,308

Some industries do not present mass nor physical exergy flow because these are the result of using pumps, boilers and furnaces, where duty is removed. The total exergy of the outlet streams is greater than total exergy of inlet streams for industrial services, as can be seen in Table 1. Figure 3 and 4 shows exergy analysis and the efficiency for the production and refining of the crude studied, respectively.

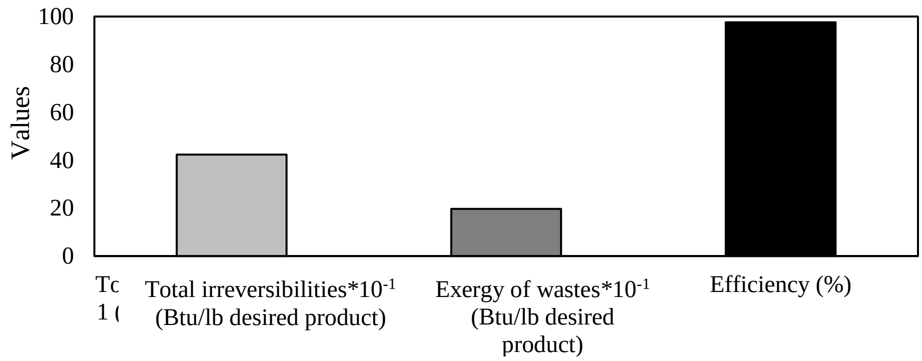

Figure 3. Exergy analysis of battery production of a Colombian crude oil

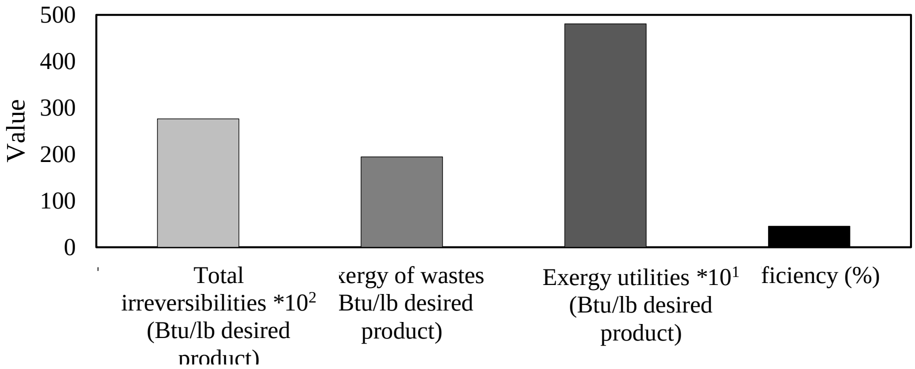

Figure 4. Exergy analysis of refining process of a Colombian crude oil

4. Conclusion

Simulation of production and refining of Caño Limón crude oil was performed using Computer Aided Process engineering. Exergy analysis in crude oil production stage was applied resulting an efficiency of 97 %, due to low exergy losses caused by process waste and not by no-used utilities. For refining step, the efficiency was 45 %, which evidences that most exergy losses occur due to the large number of utilities supplied to this process and contribution of the waste in it, with a total of 564,197,267 Btu/h for a production of 1,000 barrels per day at the refinery. This indicates that energy process integration is necessary to reduce the high consumption of utilities and thus reduce these losses.

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