Thermodynamic optimization of an entire crude oil distillation unit

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Abstract

The energy use of the crude oil refining industries has risen over the years. This work deals with the simulation, thermodynamic analysis and optimization of an entire crude oil distillation unit (CDU) composed of an atmospheric distillation unit (ADU), a vacuum distillation unit (VDU), Train heaters (TH), Stabilizer Unit (SBU) and Splitter Unit (SPU). The obtained results showed that the total exergy losses are about 120 MW for a crude flow rate of 561t.h^{-1}: 69% of those losses are located in the ADU, 21.5 % in the VDU, 7 % in the exchange trains, 2 % in The stabilization column and 0.5% in the splitter column. The efficiency of the furnace and that of the atmospheric and vacuum column prove that these equipments can play an important role in improving the unit performance. An optimization study of atmospheric and vacuum unit was carried out by adjusting operating parameters to maximize efficiency. Results showed a considerable economic benefit at no additional cost of equipment without trading off the products qualities.

Keywords:* *Crude oil distillation, energy, exergy, simulation, efficiency, optimization

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I. INTRODUCTION

Crude oil distillation is the most important step in petroleum refining. Indeed, the energy required for this operation represents between 35and 45% of the energy consumed in a refinery [1]. A crude distillation unit (CDU) consists of an atmospheric distillation unit (ADU), an optional preflash unit (PFU), a vacuum distillation unit (VDU), Train heaters (TH), a stabilizer unit (SBU) and a splitter unit (SPU). Typical products of a crude distillation unit are light and heavy naphta, kerosene, diesel, atmospheric gas oil (AGO), light vacuum gas oil (LVGO), heavy vacuum gas oil (HVGO) and vacuum residue.

In recent years, the analysis of crude oil distillation has received considerable interest. A number of studies are available in the literature proposing solutions to improve its energy efficiency at low cost. Most success are in energy recovery increasing by the optimization of the heat exchanger networks associated to the CDU [5]. Other solutions are considered by using preflash devices [6,7,8]. In this way, it is possible to reduce furnace consumption and to have an improvement of the heat exchanger network [8].

Most of previous studies are only focused on reducing energy loss. However, attention has to be attributed to the quality of energy besides its quantity in order to comprehensively evaluate the utilization efficiency of energy [9]

Therefore, exergy analysis is used to evaluate the energy performance of processes. It allows to identify the areas of energy improvement potentials and to study the influence of thermodynamic factors on the efficiency of the process. Few academic researchers used exergy analysis in crude distillation units to identify those areas. But, these studies were limited to one or two sections of the crude distillation unit; For example, the exergy analysis conducted in [10], and [11], were limited to the ADU and VDU units. They showed that furnaces have the highest contribution in exergy losses. An exergetic analysis of an atmospheric unit was carried out in [12, 13]. They proposed an improvement by the integration of many flashes in the preheating train. F.N. Osuolale at al, [4] has focused in optimization of atmospheric distillation column parameters by applying the sequential quadratic programming methodology.

This paper presents a simulation and a thermodynamic analysis of an entire crude distillation unit to study energy and exergy efficiencies systems. An optimization of the crude distillation units is then done by varying operating parameters to minimize exergy loss without trading off the products qualities and process throughput.

II. PROCESS DESCRIPTION

Real data were collected to obtain a reliable simulation of the unit. Most of operation conditions are based on an existing refinery in Tunisia. Fig.1 shows a schematic diagram of the crude unit distillation under study. In order to reduce the viscosity and allow a better operating efficiency in the desalting unit, the oil is preheated through a preheat train (train A) to about 120 ° C. Once desalted, the crude is pumped through a second preheat train (train B) where it reaches about 255 ° C before going to the furnace. The crude oil is heated to 350°C in this equipment then sent directly to the atmospheric distillation tower where it is separated into different fractions. The main products of this column are naphta, kerosene, diesel, atmospheric gas oil (AGO) and atmospheric residue. Naphtha is cooled, condensed and routed as liquid to the stabilizer column. The stabilized naphta is then transferred to the splitter column to separate the light gasoline from the heavy gasoline. The side products (kerosene, diesel, atmospheric gas oil (AGO)) are stripped in the side strippers with the stripping vapor. The bottom residue is sent to the vacuum furnace where it is heated to 400°C before being transferred to the vacuum distillation tower. The side cuts of this column are light vacuum gas oil (LVGO) and heavy vacuum gas oil (HVGO). The vacuum residue leaves from the bottom of this column and undergoes further treatment in the refinery.

This unit has as capacity of 100 000 barrel per day of Zarzaitine (Tunisia) and Es seider (Lybia) crude oil mixture.

Table 1: Properties and composition of light components of the crude oil

Parameter	Value
API	34.5
Density ($kg.m^{-3}$)	848.3
Viscosity (cP)	7,94
Propane (Wt%)	0.01
i-Butane (Wt%)	0.09
n-Butane (Wt%)	0.49
i-Pentane (Wt%)	0.47
n-Pentane (Wt%)	0.85

III. SIMULATION

The process was simulated using ASPEN HYSYS. The main steps of this simulation are:

- Introduction of pure and hypothetical components
- Selection of the fluid package to be used for the estimation of the thermodynamic properties. The property package selected in this case is the Peng Robinson model.
- Building the flowsheet of the distillation unit
- Entering the characteristics of the crude oil and the operating parameters needed for the devices.
- Running the simulation.
- Recovery and exploitation of results.

The most important parameters to be entered in this simulation are temperature, pressure, composition and flow rates for each feed stream. For the equipment, we need to enter mainly the number of trays for each column and the flowrates and duties for pump-around circuits.

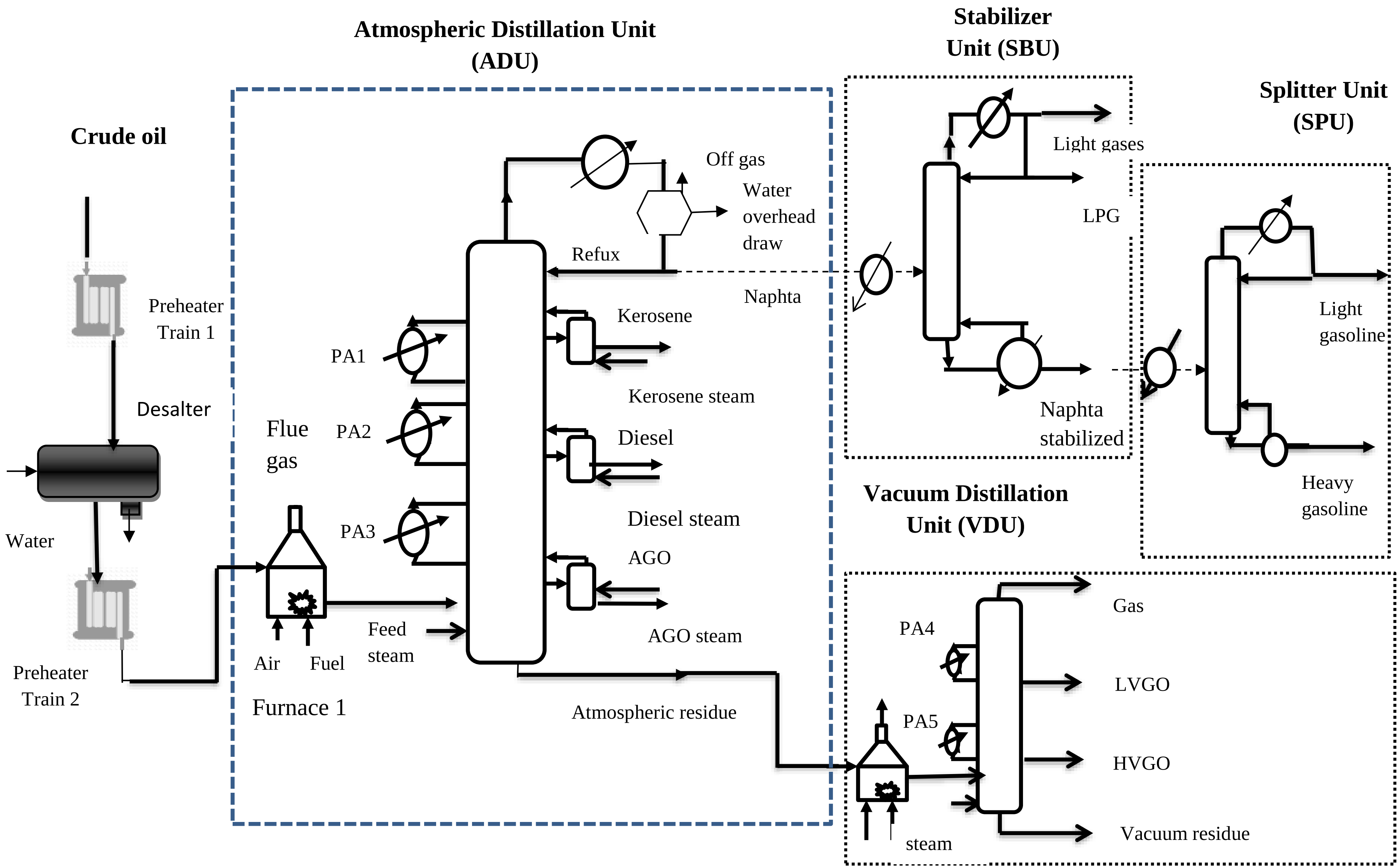

Fig.1: Flowsheet of the crude unit distillation

IV. ENERGY AND EXERGY ANALYSIS

IV.1. ASSUMPTIONS

In order to carry out our study, the following assumptions were made:
- The system is in a steady state.
- Potential and kinetic energies are negligible [14, 15].
- The reference state is T = 298.15 K and P = 101 kPa (The widely accepted reference environment defined by Szargut [16, 17])

VI.2. ENERGY AND EXERGY BALANCE EQUATIONS

Equations used in thermodynamic analysis to study energy and exergy efficiencies are the mass conservation equation, the energy conservation equation, and the entropy generation equation. Energy analysis is carried basing on the first law of thermodynamic which expressed the principle of energy conservation. Exergy analysis is a technique combining principles of mass and energy conservations which provides information about irreversibility occurring within a system.
After simplifications, the mass, energy, and exergy balance equations, respectively, are [10, 18, 19]:

$$\sum_{In} \dot{m}_{in} = \sum_{Out} \dot{m}_{out} \quad (1)$$

$$\sum_{In} \dot{E}_{in} + \dot{Q}_{cv} - \dot{W}_{cv} = \sum_{Out} \dot{E}_{out} \quad (2)$$

$$\sum_{In} \dot{Ex}_{in} + \sum_{j} \dot{Q}_{cv}\left(1 - \frac{T_0}{T_j}\right) - \sum_{Out} \dot{Ex}_{out} - \dot{W}_{cv} = I_{cv} \quad (3)$$

Where $\dot{m}$ is the mass flow rate, $\dot{E}$ is the steam energy rate, $\dot{Q}_{cv}$ is the heat rate into the control volume, $\dot{W}_{cv}$ is the work done by the control volume, $\dot{Ex}$ is steam exergy rate and I_{cv} is the irreversibility

IV.3. EQUATIONS

IV.3.1. EXERGY TERMS

As the kinetics and potential exergies are negligible, the total exergy of a stream can be written as:

$$Ex_{total} = Ex_{phy} + Ex_{chem} \quad (4)$$

Where Ex_{phy} stands for physical exergy and Ex_{chem} for chemical exergy

- *Physical exergy*

The physical exergy is calculated as:

$$Ex_{phy} = H - H_0 - T_0(S - S_0) \quad (5)$$

where H is the specific enthalpy, S is the specific entropy and T is the temperature. The subscript 0 denotes reference conditions.

- *Chemical exergy*

The chemical exergy is equal to the maximum amount of work obtainable when the substance under consideration is brought from the environmental state, defined by the parameters T_0 and P_0, to the reference state by processes involving heat transfer and exchange of substances only with the environment. The chemical exergy is given by [11, 19].

$$Ex_{chem,i} = \sum x_i\, Ex^\circ_{chem,i} + R\,T_0 \sum x_i\, Ln\, \gamma_i x_i \quad (6)$$

where xi is the mole fraction of the i component in the mixture, $Ex^\circ_{chem,i}$ denotes the standard chemical exergy of the i component , and γ_i is the activity coefficient of the i component.

For identified components the standard chemical exergy can be found in literature but for pseudo components following equation is applied [16]:

$$Ex^\circ_{chem,i} = \beta\ LHV \quad (7)$$

where β is the ratio of the chemical exergy to the lower heating value LHV. β can be estimated as a function of the atomic ratio of carbon to hydrogen H/C according to Eq (5).

$$\beta = 1.0406 + 0.0144\,\frac{H}{C} \quad (8)$$

where $\frac{H}{C}$ is calculated by using Eq.(6)

$$\frac{H}{C} = \frac{11.9147}{(8.7743*10^{-10}.\varepsilon.T_b^{-0.98445}.\ SG^{-18.2753})} \quad (9)$$

where T_b is the boiling temperature, SG is the specific gravity and ε is given by:

$$\varepsilon=\exp(7.176.10^{-3}.\ Tb + 30.06242\ .SG - 7.35.10^{-3}.Tb.SG) \quad (10)$$

LHV is determined by Eq (8):

$$LHV = \frac{1}{0.429923}\,(16840+76.60\ API - 1.230API^2 + 0.008974\ API^3)(\ kJ/\ kg) \quad (11)$$

Where API is American Petroleum Institute gravity

IV.3.2. ENERGY AND EXERGY EFFICIENCY

The energy efficiency is calculated as [10]:

$$\eta=\frac{\dot{E}_{product}}{\dot{E}_{feed}} \quad (12)$$

The exergy efficiency is calculated by [17, 18]:

$$\varphi = \frac{\sum Ex_{out}}{\sum Ex_{in}} \quad (13)$$

Where: $\sum Ex_{in}$ is the total inlet exergy, $\sum Ex_{out}$ is the total outlet exergy

IV.4. PROCESS OPTIMIZATION

The objective of the optimization is to minimize exergy loss of the crude distillation unit. The first simulation was conducted based on the operating conditions described in the paragraph 2. Then, the effect of the operating parameters on efficiency and exergy losses is studied for the main process equipment. The optimization was carried using the optimizer tool built in ASPEN HYSYS. [22] The objective function is defined as the exergy loss. Variables and constraints are setting following the unit specifications.

In the ADU column, this function is a vector of decision variables which are: pump-around flow rate, pump-around return temperature and steams flow rates. The quality of the ADU straight run products are entered as ASTMD86 specifications as shown in table 2.

Table 2: ADU specifications

Product	ASTM D86 95% (K)
Naphta	483
Kerosene	541
Diesel	599
AGO	710

The optimization variables used for the VDU are the flow rate of the bottom steam, pump-around flow rate and pump-around return temperature.

Table 3: ADU specifications

Product	ASTM D86 95% (K)
LVGO	613
HVGO	818

For the ADU and the VDU furnace, the temperature and the pressure in each unit are treated. The following constraints are taken:

$$(T_{furnace})_{min} < T_{furnace} < (T_{furnace})_{max}$$
$$(P_{furnace})_{min} < P_{furnace} < (P_{furnace})_{max}$$

V. RESULTS AND DISCUSSION

The results obtained from the first simulation were used to evaluate energy and exergy efficiency and losses for each equipment.

V.1. ENERGY ANALYSIS

The total energy used in the CDU is about 110 MW (fuel to furnace and energy supplied to the splitter and stabilizer reboiler). The plant energy analysis shows that the large proportion of energy input was lost in the cooler and condenser. (Fig2.). More information can be obtained by examining the pattern of components in each unit.

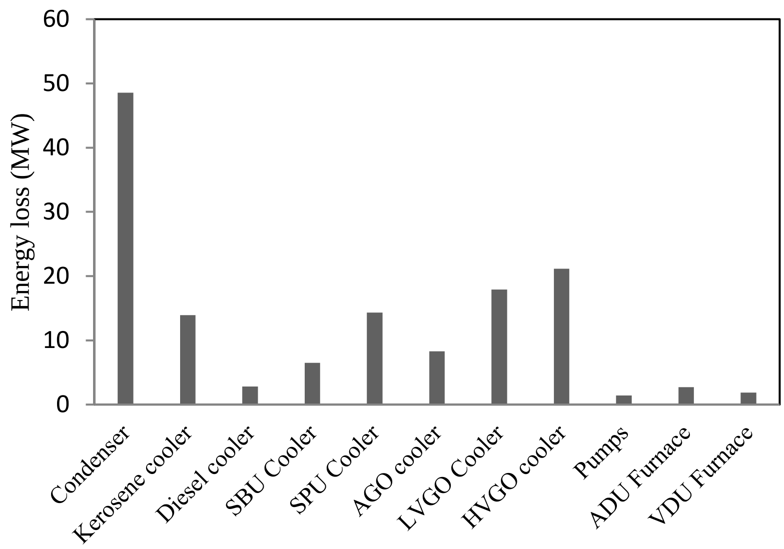

Fig.2: Energy losses in the different components of the CDU

For the ADU unit, the energy balance for the atmospheric distillation column analysis shows that an important proportion of energy input was lost in the cooler and condenser. The energy loss in the coolers and condenser is about 96% while the contributions are only 3.6% and 0.4 % respectively for the ADU furnace and pumps.

The energy efficiency of the ADU column is about 55.97 %. The available energy in the outlet steams of the column are used in the train heat exchanger. The furnace energy efficiency is about 96%.

For the VDU unit, the energy efficiency of the VDU column is about 68%. The ADU column energy efficiency is lower since the main separation takes place there.

The energy balance for the train heater, SPU and SBU is satisfied. Therefore efficiency is not defined.

The energy efficiency of crude distillation units was reported by [10] and [1] the energy efficiency of the ADU and VDU column by ref [10] are respectively 49.7 and 57.9% and those by [1] are about 55.6% for the ADU and 78.9 % for the VDU. Differences in value in these works can be attributed to the differences in system efficiency definitions, configuration and plant operating conditions.

The energy analysis reveals the area of energy loss but provides no information about the irreversibility of the process. An exergetic analysis is therefore performed.

V.2. EXERGY ANALYSIS

The exergy analysis revealed that the highest exergy losses in the plant are located in the atmospheric distillation unit followed by the vacuum distillation unit, the Train Heater, the stabilization column and the Splitter column. The distribution of exergy losses in the different components is presented in Fig. 3:

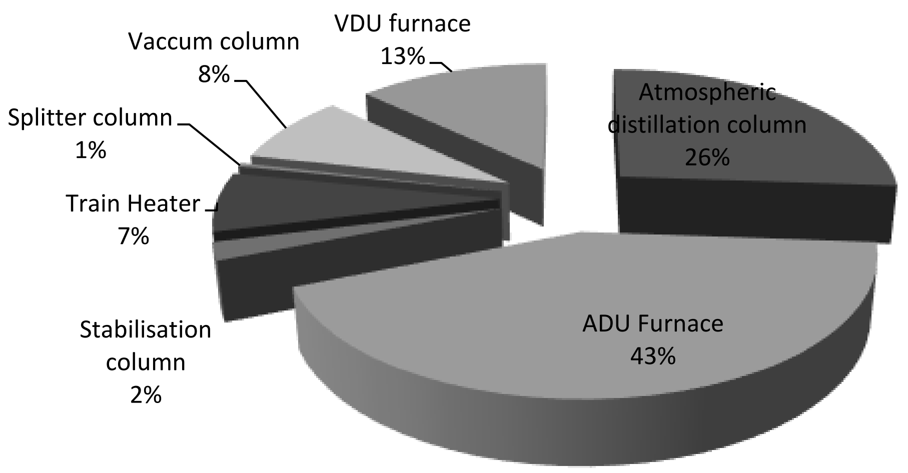

Fig.3. Distribution of exergy losses in the different process components

In the atmospheric distillation unit (ADU), the irreversibility is divided between the furnace (42.8%) corresponding to 51.09 MW and the atmospheric distillation column (26.14%) corresponding to 31.2 MW. The exergy loss in the ADU furnace can be attributed to the irreversible nature of the combustion reaction as well as the big difference between flame temperature and crude temperature. Furthermore, significant exergy losses are recorded in the atmospheric distillation column. Indeed, in the case of multi-component distillation, the liquid -vapor contact generates exergy destruction which can be attributed to mass transfer or heat transfer (the heating of the liquid and the cooling of the steam) [12].

Exergy losses in the vacuum distillation unit (VDU) are fairly important, 12.95 % in the VDU furnace and 8.38 % in the vacuum column. It is lower than those of ADU because the main separation takes place there. [10]

In the two heater trains, the irreversibility losses are about 7% which corresponds to 8.49 MW. The exergy losses of the stabilization and splitter column represent 2.12 and 0.44 % of total losses corresponding respectively to 2.5 and 0.53 MW.

Exergy loss of both columns is mainly entropy generation occurring within the system due to the variations between the operating conditions of the feed and the products steams [1]

The exergetic efficiency of the different process components is presented in fig. 4:

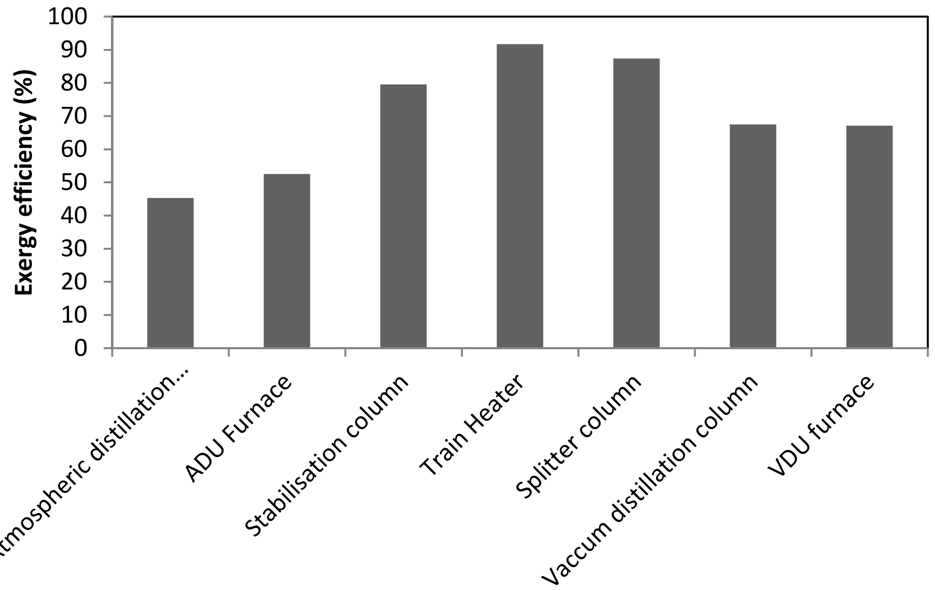

Fig. 4: Exergetic efficiency of the different components of the crude distillation unit

The exergetic efficiency of the ADU furnace is equal to 52.5 %. The corresponding exergy loss was estimated at 31.3 MW.

The exergetic efficiency of the atmospheric column, which amounts to 45.26 %, shows that this equipment can be a subject of improvement in energy performance. This can be done through investigating temperature and pressure profiles. Indeed, the temperature profile in the atmospheric distillation column is controlled by the circulating reflux. Thus, it is interesting to study of the effect of the circulating refluxes flow rate and of temperature of return of the circulating refluxes on exergy losses.

In the VDU, the exergetic efficiency of the vacuum column is equal to 67.45 % with a loss of 10 MW approximately. The exergetic efficiency of the VDU furnace is 67.12 %.

The exergetic efficiency of the stabilization and splitter columns are of 79.5and 87.4%, respectively. The feed streams to both units were preheated to reduce the irreversibility losses.

All previous work on exergy analysis of the crude distillation unit revealed that the highest exergy loss was detected in the ADU followed by the VDU and the heat exchanger. Only, the values for each component differ from one work to another. Such variations are due to the use of different flowsheets and different operating parameters and the type of crude.

The results of [10], showed that the highest irreversibility's occurred in the ADU with 56% of the total irreversibility losses. The difference can be attributed for the variation in operating parameters and type of crude. They obtained 26% for the VDU and 18% for the heaters. The exergy efficiencies of components are 43.3 % for the ADU 50.1 % for the VDU, 82.1 % for the TH 1, and 95.6 % for the TH 2. These values are close to those found in this study.

M. A. Waheed et al; [15] presented an exergy analysis of crude unit distillation which contains a preflah subunit. Their analysis revealed that the highest exergy losses of the studied plant occurred in the ADU which is 52.3%, PFU (19.3%), TH (18.6%), VDU (7.5%), SPU (1.6%) and SBU (0.2%). The exergetic efficiencies were 26.3% for the ADU 31 % for the VDU, 65.6.1 % for the SBU, and 33.7 % for the SPU. These values are much lower than the values found in this study because the exergy efficiency has been calculated using the rational approach.

Exergetic Analysis performed by R. Rivero et al; [21] showed that the atmospheric section has the highest total exergy losses (60.54%) and it is due to its low effectiveness (24.48%) that this section also has the highest improvement potential. The major part of exergy losses was found in the furnace. The effectiveness of the vacuum section was 44.69% for the section. The most effective section is the preheating and desalting section. The corresponding exergy efficiency was 82.47%. The exergy efficiency of the stabilizer unit was much lower (5.38%) than the value found in our study.

However, it is important to note that since the use of different configuration and different operating conditions, it is hard is difficult to explain these differences.

According to this analysis, the ADU and VDU unit distillation are the most in need for improvements.

V.3. SENSITIVITY ANALYSIS

Pump-arounds are used to control the temperature profile of the distillation column and hence the quality of separation. Thus, their effect on exergy losses in the ADU and VDU distillation columns is interesting to investigate.

The ADU column has three pump-around circuits, namely PA1, PA2 and PA3. Figures 5 and 6 illustrate the effects of changing the flow rate and return temperature of PA1 on the exergy losses and efficiency of the ADU.

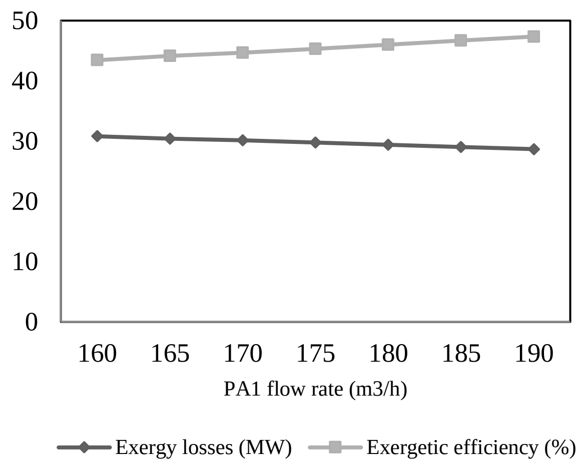

Fig.5. Effect of adjusting PA1 flow rate on exergy losses and exergetic efficiency of the atmospheric column

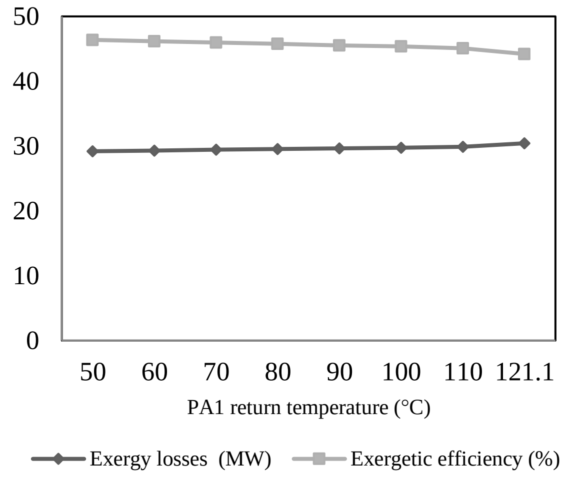

Fig.6. Effect of adjusting PA1 return temperature on exergy losses and exergetic efficiency of the atmospheric column

By increasing the mass flow of the circulating reflux, the loss of exergy decreases and the exergy efficiency increases. A reduction of 7% is obtained when the PA1 flowrate goes from 160 to 190 $m^3.h^{-1}$. This corresponds to 4% increase in the exergy efficiency according to figure 6. Moreover, exergy losses increase by 5 % when the PA1 return temperature goes from 50 to 120°C. This corresponds to a 3% decrease in the column efficiency. The same behavior was observed for all other pump around PA2, PA3.

The effect of feed steam flow rate is shown in figure 7. According to this figure, an 8% reduction in exergy efficiency is observed when the steam flowrate is increased from 7000 to 9000 $kg.h^{-1}$.

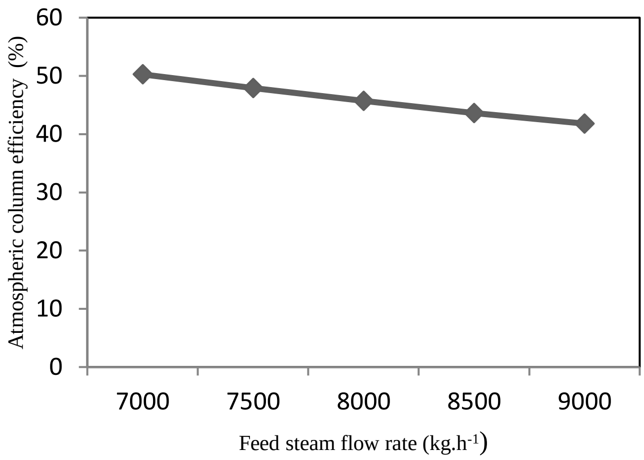

Fig. 7: Effects of changing the flow rate of the feed steam on the exergy efficiency of the atmospheric distillation column

The increase of the furnace outlet temperature beyond 350°C, the furnace exergetic losses and the duty decreases slightly. On the other hand, with a temperature lower than 350°C, the exergetic losses decrease considerably. It is important to notice a variation of the mass flow rates of the various compounds at the exit of the column especially an increase of the flow of the residue and a decrease of the flow of diesel. In this case, it could be better to improve the middle distillate and reduce the residue flowrate. Therefore the $T_{furnace})_{max}$ is fixed at 350 °C as in the optimization.

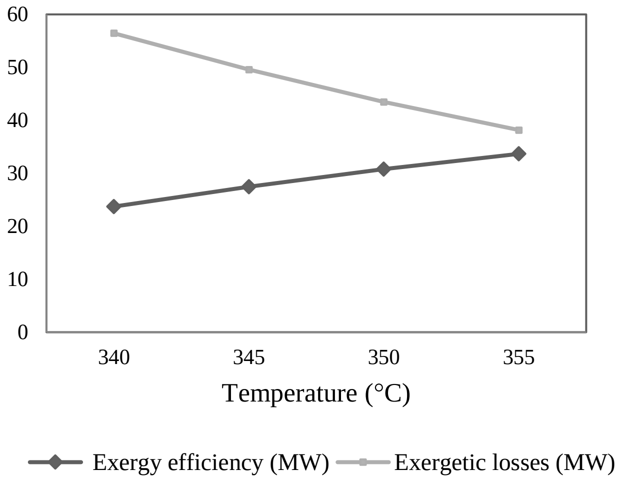

Fig. 8: Effects of changing the furnace outlet temperature on the exergy loss and efficiency of the atmospheric distillation column

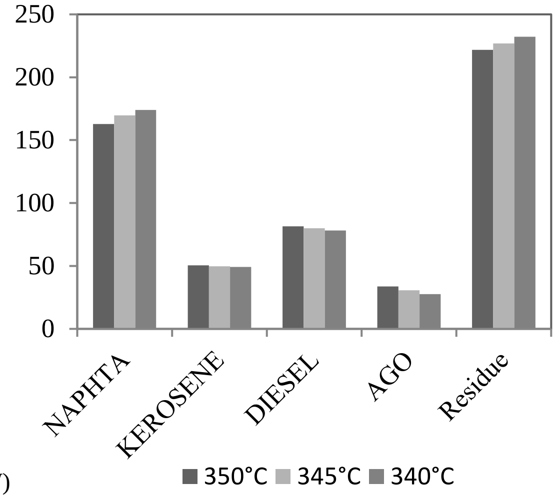

Fig. 9: Effects of changing the furnace outlet temperature on the atmospheric distillation column product flow rates

V.4. THERMODYNAMIC OPTIMIZATION DESIGN

Parameters optimization was carried using the Aspen Hysys optimizer tool. The total exergy loss was minimized in the ADU and VDU unit with the following manipulated parameters: pump-around flow rate, pump-around return temperature, steams flow rates, temperature and pressure of the furnace.

No significant differences were observed in flow rates of the ADU products but their quality was improved as shown in table 4.

Table 4.: ASTM D86 distillation of ADU products

Process	Naphta %5 vol, °C	Kerosene %5 vol, °C	Diesel %5 vol, °C	AGO %5 vol, °C	Residue %5 vol, °C
Reference process	70.91	222.14	267.17	317.76	344.88
Optimized process	70.87	220.92	259.40	308.78	325.89

The most important results of the modifications realized on the ADU are summarized in table 5. It is clear that a considerable savings can be made with the optimization of the operating conditions in the ADU section. As a result of optimization, the exergy loss decreased by about 22 % in this unit. They dropped from 79.39 MW to about 61.9 MW. As a consequence, the steam consumption decreased by about 12% leading to important saving in operating costs. The optimization of the VDU unit, as summarized in table 6, led to a reduce of exergy loss from 25.6 to 19.76 MW. Exergetic loss decreased as furnace duty decreases. The vacuum column becomes more reversible without varying product quality. The results of F. N. Osuolale et al; [4], showed a total profit increased by 2.63 10^5 \$/yr due to the optimum operating conditions from the exergy analysis of the column. The results of C. Yan et al; [9], showed that the exergy loss ADU and VDU are respectively reduced from, 37483.07 kW, and 25194.52 kW to 34926.76 kW, and 25115.94 kW by optimizing the operational temperature and pressure conditions of furnace, the flow rate of bottom streams of the columns, and side-strippers steam. The differences in value can be attributed to the difference in the initial conditions of operation of the plant. Nevertheless, the proposed method can be applied to any systems as long as the systems operational data are available and the exergy efficiency of systems can be then optimized.

Table 5: Comparison between the reference ADU unit and the optimized one

	Reference process	Optimum process
Furnace temperature (°C)	350	350
Furnace pressure (bar)	2.73	2.75
Furnace duty (MW)	69.025	69.00
Streams (kg/h)	12473.83	10019.811
Atmospheric column exergy loss (MW)	32.47	14.64
Atmospheric column exergetic efficiency (%)	40.3	70
Atmospheric column energy efficiency (%)	55.97	65.12
Unit exergy loss (MW)	79.39	61.9
Saving	$3.6\ 10^5$ \$/yr	

Table 6: Comparison between the reference VDU unit and the optimized one

	Reference process	Optimum process
Furnace temperature (°C)	404.44	394
Furnace pressure (bar)	0.23	0.23
Furnace duty (MW)	21.8	19.23
Streams (kg/h)	9072	9072
Vacuum column exergy loss (MW)	10.02	6.63
Vacuum column exergetic efficiency (%)	67.45	78.16

Unit exergy loss (MW)	25.6	19.76
LVGO %5 vol, °C	302.80	313.28
HVGO %5 vol, °C	373.52	365.42
Saving	$8.6\ 10^{5}\ \$/\mathrm{yr}$	

VI. CONCLUSION

The objective of this work was to perform a thermodynamic analysis on a crude oil distillation unit to study energy and exergy efficiencies for system analysis, performance evaluation and optimization. The unit's inefficiencies were identified especially in the ADU with the highest losses in the furnace. Our analysis showed that this unit has a significant potential for improvement in exergy performances. Moreover, it was found that a parametric optimization led to important reduction in exergy losses and saving consumption in both ADU and VDU unit. Results showed a considerable economic benefit at no additional cost of equipment. This will be a good tool in the hand of chemical engineers for the operation of efficient distillation unit. The proposed analysis and optimization can be used as long as the operational conditions are given. In this work product quality constraints on the columns are introduced to give as close as possible to what obtains in reality. Finally, this study would serve as useful data especially for the revamping of the Tunisian refinery which is fairly outdated.

NOMENCLATURE

β Ratio of the chemical exergy
E Energy rate, MW
Ex Exergy rate, MW
H Enthalpy, $KJ.Kmol^{-1}$
I Irreversibility, MW
P° Reference pressure, kPa
Q Heat rate, kW
S Specific entropy, $kJ.\ kmol^{-1}\ K^{-1}$

φ Exergy efficiency,%
T° Reference Temperature, K

W Work, kW

ABBREVIATIONS

ADU Atmospheric Distillation Unit
AGO Atmospheric Gas Oil
API American Petroleum Institute
ASTM American Society for Testing of Materials
CDU Crude Distillation Unit
LHV Lower Heating Value
PA Pump Around
SBU Stabilizer Unit
SG Specific Gravity
SPU Splitter Unit

TH Train Heater

SUBSCRIPT

b boiling
chem chemical
cv Control volume
° Reference conditions
in inlet
out outlet
ph physical

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