Optimization of Energy Consumption and CO_2 Reduction of Distillation Column in Oil Process

Ahmed Ould Brahim, Souad Abderafi

***Abstract*—**The separation of petroleum fractions are energy and power intensive processes and contribute significantly to the greenhouse gases emissions (e.g. carbon dioxide). The main objective of this study is to get a better use of energy and reduce impact environmental, for the distillation column of petroleum fractions, especially the gasoline stabilization column. To do this, the steps followed for the calculation of distillation columns were presented. Simulations result using Soave-Redlich-Kong (SRK) thermodynamic model, with the help of CHEMSEP and Pro II softwares were validated on the basis of experimental data collected from crude oil refinery. Hence, a technical feasibility study was carried out, using numerical simulation, to run the stabilization column at optimum values of pressure, reflux ratio and feed tray to optimize the energy consumption. Then the energy consumption, energetic efficiency and carbon dioxide emissions from the furnace (Reboiler) of the column were calculated, before and after optimization. The results allowed us to highlight the effect of these parameters on the energy consumption of the stabilization column. From an economic point of view, stabilization column with optimal parameters may contribute to a decrease in expenses related to the energy consumption and carbon dioxide.

***Keywords*—** Impact Environment, CO2 emission, Optimization, Energy consumption, modeling, columns parameters, gasoline stabilization column

I. INTRODUCTION

Climate change affects all regions of the world and the last 30 years have seen the highest temperatures. This climate change can cause serious damage to the health, a considerable impact on agriculture and environmental pollution. The international commitment to keep the increase in average temperatures to well below two degrees Celsius (2°C), relative to pre-industrial levels, will require substantial and sustained reductions in global emissions. The 196 Parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed on a long-term global objective, as part of the package of decisions at COP16 in Cancun in December 2010 to COP22 Marrakesh November 2016 [1]. Greenhouse gas emissions from the energy sector account for about two-thirds of all human-caused emissions of greenhouse gas and the CO2 emissions from sector have increased over the past century at ever higher levels [2]. Reducing CO2 emissions is an absolute necessity and expensive challenge to the chemical process industries in order to meet the environmental targets as agreed in the Kyoto Protocol [3]. Among these energy sectors, distillation process is considered as the primary separation process used in industrial chemical processing. While, it has many advantages, the significant energy requirement is one major drawback which can significantly influence overall plant profitability. It is quite energy intensive and accounts for a large part of industrial energy consumption and CO2 emission [2,4]. Increasing energy costs deter energy consumption as do tighter environmental regulations regarding fossil fuel use, leading to research into new and more efficient separation methods [4, 5]. Effective action in the energy sector is therefore essential in the fight against the climate change problem. In the light of the emissions associated with fossil fuel combustion and their associated health and environmental impacts the optimization of the energy consumption is important with reduce the CO2 emission and environment impact. Recently, energy and environmental sustainability assessment of a crude oil refinery were studied by using thermodynamic analysis [6]. The objective of this work attempts to optimize energy consumption and reduce CO2 emissions, for the distillation column, especially the stabilization column of a refinery. The methodology used in this study will be based on the test of parametric sensitivity of the stabilization column.

II. DESCRIPTION OF PETROLEUM PROCESS

The petroleum is a complex mixture of different hydrocarbons fractions, small amounts of sulfur and trace amounts of oxygen, nitrogen and metals. Separation is effected by heated the mixture to an elevated temperature of about 400°C, then injected into an atmospheric pressure distillation column. Distillation is the separation of completely miscible mixtures of liquids according to the difference of the boiling point and volatility of the components in the mixture. However, the lighter products, as butane, are obtained at the head of the column and the heavier components such as gasoline, kerosene and gas oil (diesel oil) remains successively lower [7]. As for the residue that cannot be distilled, even at very high temperatures remain at the bottom of the distillation column. Of the tray 13 of distillation column is drawn off the naphtha which feeds stabilization column. The purpose of the latter is to achieve the separation of the total naphtha in its various constituents and prepare the load of catalytic reforming [7]. Stabilization column is equipped with a partial condenser, 30 bubble cap trays and a reboiler (Figure 1).

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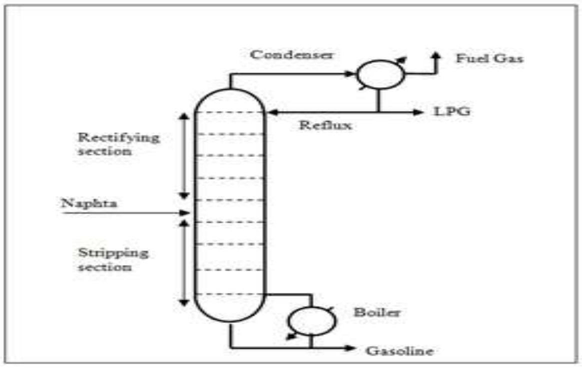

Fig. 1. Diagram relating to the stabilization colum

Stabilization column operation is similar to that of the atmospheric distillation column, except that it does not have the side streams. The power supply is disposed at the sixteenth tray (the trays are numbered from top of the column to bottom of the column). The effluent recovered at the column head is the fuel gas. At the first tray level of this column, we obtain the LPG consisting, principally of propane and butane. At the bottom of this column, we get a cut of heavy gasoline containing hydrocarbon chains type C6, C7, C8, C9 and C10 [8]. Carbon dioxide is generated mainly from furnaces, gas turbines and boilers. These utility devices are the energy consumers in the refining plants and are used to provide heat, steam and power to the process by burning a fuel. Therefore these units are key drivers in energy savings oriented projects and reducing environmental emissions impacts. Fuel is combusted when mixed with air, producing CO_2 (Figure 2) [9].

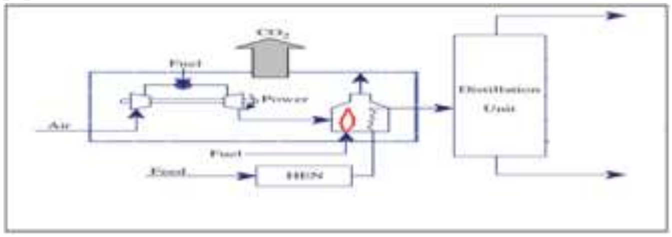

Fig. 2. Principle of CO_2 emission on reboiler [9]

A. Equations of modelling

The set of equations that govern the operation of the column is obtained using the equations of balance material, energy and the equations relating to conditions of Vapor-Liquid Equilibrium (VLE). Figure 3 shows the diagram for principle of an equilibrium stage. Each stage, j receives a diet feed Fj, a fluid flow, Lj-1 from the upper stage and a steam flow, Vj+1 of the lower stage, a liquid extraction Uj, a steam extraction Wj and a heat input Qj can be considered [10]. All these equations required for modeling are written, at each tray of the column and are given below:

- Material balance equation is given by:

$$L_{j-1}x_{ij-1} - (V_j + W_j)y_{ij} - (L_j + U_j)x_{ij} + V_{j+1}y_{ij+1}F_j z_{ij} = 0 \quad (1)$$

- Energy balance equation is given by:

$$L_{j-1}h_{j-1} - (V_j + W_j)H_{ij} - (L_j + U_j)h_j + V_{j+1}h_{j+1}F_j h_{Fj} - Q_j = 0 \quad (2)$$

Where, V and L are vapor and liquid flow rate, respectively (in kg/h); U and W liquid and vapor side stream flow, respectively (in kg/h).

- The heat quantities in the boiler and in the condenser are calculated from the following equations:

$$Q_1 = V_2 h_2 - (U_1 + L_1)h_1 - V_1 h_1 \quad (3)$$

$$Q_n = V_n h_n + U_n h_n - L_{n-1}h_{n-1} \quad (4)$$

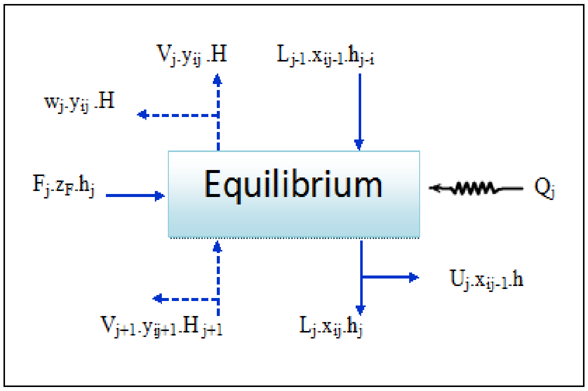

Fig. 3. Principle of an equilibrium stage

Where, Q_1 is heat flow of condenser and Q_n is heat flow of reboiler.

B. Calculation of VLE

The calculations of VLE are realized by mean of equality of temperature, pressure and fugacity in each liquid and vapor phase. The equation of the latter is written as:

$$f_i^L = f_i^V \quad (5)$$

Where f_i^V and f_i^L are fugacities of component, i in vapor and liquid phase, respectively, at the same temperature and pressure, expressed by:

$$f_i^L = x_i \varphi_i^L P \quad (6)$$

$$f_i^V = y_i \varphi_i^V P \quad (7)$$

Where, x_i and y_i are the liquid and vapor phase mole fraction of component and φ_i, is fugacity coefficient of component, i.

Thermodynamic model

VLE calculation requires a thermodynamic model like an equation of state (EOS). Among the many cubic EOS of Van der Waals type currently available, the equation proposed by Soave-Redlish- Wong (SRK) is widely used due to its simplicity and flexibility, for hydrocarbons fractions [11]. This model has the following form for a pure component [12]:

$$P = \left(\frac{RT}{V-b} - \frac{a(T)}{V(V-b)} \right) \tag{8}$$

Where, P is the absolute pressure, T is the absolute temperature, V is the volume and R is the ideal gas constant. The volume and energy parameters of the SRK EOS (a and b), are calculated from the following equations:

$$b = 0.086640 \frac{RT_c}{P_c} \tag{9}$$

$$a(T) = 0.42748 \frac{(RT_c)^2}{P_c} \left(1 + m\left(1 - \sqrt{T_r}\right)\right)^2 \tag{10}$$

Where, subscripts c and r denote critical and reduced conditions, respectively; m depend on the acentric factor, ω:

$$m = 0.48 + 1.57\omega + 0.172\omega^2 \tag{11}$$

For extending SRK EOS to mixtures, it is necessary to include composition. Many algebraic relations have been suggested for this purpose. We elected to choose those recommended for SRK EOS [8]. They are the classic Van der Waals one-fluid mixing rules, used to calculated a_m and b_m mixture parameters from:

$$a_m = \sum_i \sum_j x_i x_j \left(a_i a_j\right)^{0.5} \left(1 - k_{ij}\right) \tag{12}$$

$$b_m = \sum_i x_i bi \tag{13}$$

k_{ij} is the binary interaction parameter between component, i and j; with $k_{ij}=k_{ji}$ and $k_{ii}=0$

C. CO_2 Emissions Model

In distillation column such as stabilization unit, CO_2 is generated, mainly, from boilers or furnaces [8]. These devices are used to provide a heat and power to the process by burning a fuel. The fuel is combusted when mixed with air, producing only CO_2, according to following stoichiometric equation:

$$C_x H_Y + \left(x + \frac{y}{4}\right) O_2 \rightarrow xCO_2 + \frac{y}{2} H_2O \tag{14}$$

Where, x and y are the carbon, C and hydrogen, H, atoms number, respectively, present in the fuel compositions, and where complete oxidation of carbon is assumed.

The heat and power generating devices used are fired heater (furnace), boiler. This device is source of CO_2 emissions. Typical fuels used in this heating device are light and heavy fuel oils, natural gas. In the combustion of fuels, air is assumed to be in excess to ensure complete combustion, so that no carbon monoxide is formed. The concentration of CO_2 emissions, $[CO_2]_{Emiss}$ (kg/s), is related to the amount of fuel burnt, Q_{Fuel} in a heating device as follows:

$$[CO_2]_{Emiss} = \left(\frac{Q_{Fuel}}{NHV}\right)\left(\frac{C\%}{100}\right)\alpha \tag{15}$$

Where, α = 3.67 is the ratio of molar masses of CO_2 and C, while NHV the net heating value of fuel equal to 39,771 kJ/kg, with a carbon content of Carbon equal to 86.5 % [8].

The amount of fuel burnt in a furnace can be related to the heat duty required by the process, Q_{Proc} (kW), and the efficiency of the furnace, η_{Furn} as follows[9]:

$$Q_{Fuel} = \frac{Q_{Proc}}{\eta_{Furn}} \tag{16}$$

Through the use of a process simulator, CHEMSEP, for simulations, SRK equation of state that supports the widest range of operating conditions and the greatest variety of systems was used to predict the vapor-liquid equilibrium.

III. RESULTS AND DISCUSSION

The experimental data are used to test the accuracy of thermodynamic simulation model. These data were collected from a sample of the stabilization column (Table 1). The feed of this unit derived from the atmospheric distillation is composed of traces of H_2 and H_2S, small amounts of the hydrocarbon type C_1, C_2, C_3, C_4 and C_5, as well as a heavy gasoline fraction containing hydrocarbon chains of type C_6, C_7, C_8, C_9, C_{10} and traces of C_{11}. The Fuel Gas is recovered at the top of the column. At the first tray, the LPG is obtained, at a pressure equal to 13.7 bar. The stabilized gasoline is recovered at the bottom column, at a pressure equal to 14.1 bar. Using the SRK EOS with $k_{ij}=0$ and with the help of the Pro II, process simulation software, the calculated results are compared to the experimental data by calculating the error thanks to the following relationship:

$$E(\%) = \frac{|V_e - V_c|}{V_e} \times 100 \tag{17}$$

Where, V_c and V_e are the calculated and the experimental values, respectively.

This comparison allowed us that the results are satisfactory, if we consider the experimental error [13].

TABLE.I. EXPERIMENTAL DATA FOR STABILIZATION COLUMN

	Z_i		
Compound	Feed	Gasoline	LPG
H_2	6,97E-02		0,10137
H_2S	2,56E-03		0,02816
C_1	3,35E-02		0,08873
C_2	2,13E-02		0,08661
C_3	3,20E-02		0,15846
i C_4	2,90E-02	0,00042	0,15309
n C_4	6,49E-02	0,00135	0,34013
i C_5	7,46E-02	0,09218	0,03469
n C_5	7,69E-02	0,10214	0,00876
C_{6+}	5,950E-01	5,95E-01	5,95E-01
N (kmol/h)	84716.09	65371.6	10964.3
SG	0.65	0.74	0.60
P (bar)	19.8	14.1	13.7
T_e (°C)	132	122.5	50

A. *Optimization of energy consumption*

To get a better use of energy for the distillation column of industrial process, some parameters such, pressure, reflux ratio and feed tray must be taken into consideration in the determination of energy consumption in such systems [14]. In this section, we present the effects of all these parameters on the energy consumption, thermodynamic efficiency and the CO_2 emission environment impact of stabilization column.

- **Effect of Pressure:**

The parametric sensitivity study was tested for pressure, at the top of the column. By choosing different pressure values below 13 bar, we had tried to obtain the experimental data related to the boiling temperature, mol flow rates and the specific gravity (SG), at 15°C of LPG and gasoline. Note that, the pressure equal to13 bar is usually applied in refinery. The result allowed us to conclude that the minimum pressure required at the top of the stabilization column is 9 bar. The simulation results given for this pressure are summarized in the Table 2. This table shows that, in general the SRK EOS allows a better simulation of the T_e, N and SG for the LPG and Gasoline. For each pressure, thermodynamic efficiency was calculated and the results obtained are represented in fig. 3a. This figure represents the variation of thermodynamic efficiency with pressure and shows that the optimal value is equal to 9 bar. The optimized value of pressure and that usually applied in refinery were used to run the stabilization column and to calculate heat flow of condenser and of reboiler. The results obtained are grouped in Table 3, which shows that for the use of a pressure equal to 9 bar, the heat flow of the reboiler decreases, which enables us to save 1.2 Gcal / h.

TABLE II: SIMULATION RESULTS AT 9 BAR

	LPG		Gasoline	
	V_c	E(%)	V_c	E(%)
T_e (°C)	51.89	3.78	122.68	0.15
N (Kmol/ h)	10963	0.07	65332.08	0.06
SG	0.56	6.67	0.70	5.41

TABLE III. COMPARISON OF HEAT FLUX AT INDUSTRIAL AND OPTIMAL PRESSURE

P (bar)	Condenser (G cal/h)	Reboiler (G cal/h)
13.7	1.8	5
9	1.8	3.8

The results allowed us to highlight the effect of pressure on the separation of products. From an economic point of view, stabilization with optimal pressure may contribute to a decrease in expenses related to the energy consumption of reboiler

- **Effect of reflux ratio**

Simulation runs were carried out to calculate the variation of thermodynamic efficiency in function of reflux ratio at industrial and optimal pressure, respectively, and by keeping the other parameters fixed. The reflux ratio was varied from 1.5 to 4.5, knowing that the value of reflux ratio usually used in refinery is equal to 2. The results obtained are represented in fig.4 b.

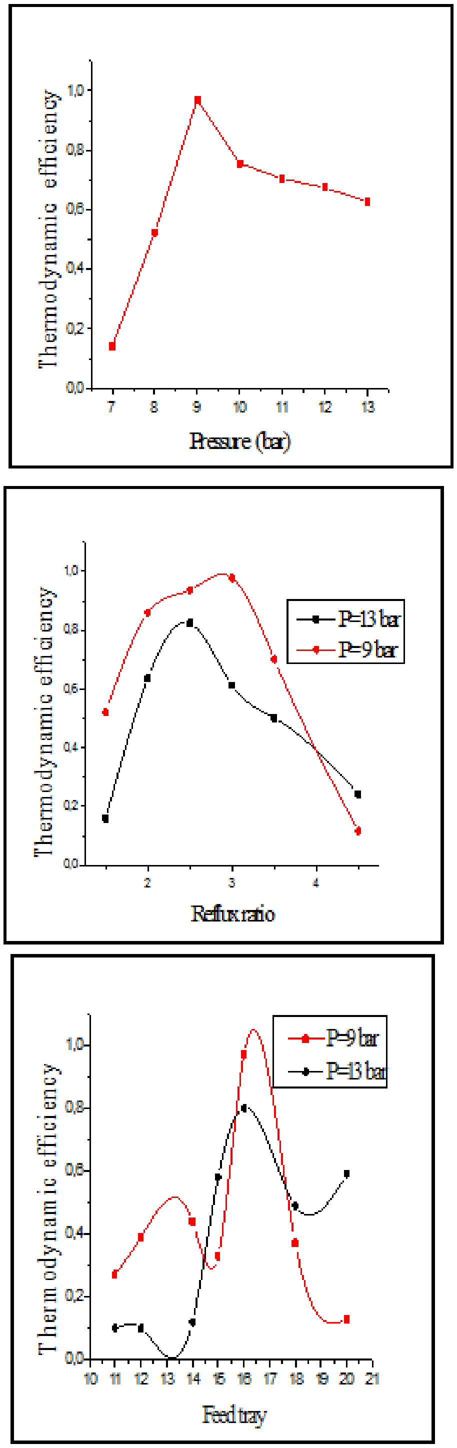

Fig. 4 : Energy efficiency en function of a)Pressure b)Reflux ratio and pressure c) Feed tray and pressure

This figure shows the comparison of variation of thermodynamic efficiency in function of reflux ratio and pressure. It is clear that for both pressure the two curves follow the same evolution but they present different maximum values. For the industrial pressure the reflux ratio is equal to 2.5 and corresponds to thermodynamic efficiency equal to 0.8; while for the optimal pressure the reflux ratio is equal to 3 and corresponds to thermodynamic efficiency equal to 1. However, we recommended to use the values equal to 3 as optimal values for reflux ratio at 9 bar.

- **Effect of feed tray of the column**

The feed tray number of the stabilization column was varied from 11 to 20 in keeping all other parameters constant and tested the two pressure studied. The results obtained are shown in fig.3c. As can be seen in this figure the two curves have different maximum thermodynamic efficiency for a feed tray number equal to 16. This is the same value that generally used in refinery but good thermodynamic efficiency is obtained for pressure equal to 9.

B. Column performance and CO2 Emission

Using equations 15 and16, the heat of reboiler, the energetic efficiency and CO_2 emission were calculated before and after optimization of the stabilization column. Table 3 presents the results obtained and shows that after optimization, there is a reduction in energy consumption, improved energetic efficiency and CO_2 Emission.

TABLE III. COMPARISON OF THE COLUMN PERFORMANCE AND CO_2 EMISSION, BEFORE AND AFTER OPTIMIZATION

Column	Before optimization	After optimization
Q_r (G cal h)	5	3,8
η	0,77	0,91
$[CO_2]_{Emiss}$ (Kg/s)	464.14	352.71

IV. CONCLUSIONS

In the present study, attention is given to get a better use of energy for the distillation column of petroleum fractions and reduction the environment impact by minimizing the CO_2 emission, especially the gasoline stabilization column. In a first time, equations to modeling this column, in the oil process are described, for each equilibrium stage. These equations are based on the mass and energy balances and VLE conditions. The SRK EOS was used to calculate thermodynamic properties of complex petroleum fluids. The accuracy of the model was tested successfully, by comparing the prediction of the boiling temperature, molar flow rates and the specific gravity at 15°C (SG) of LPG and gasoline against experimental data obtained from distillation column of Moroccan refinery.

In the second time, a technical feasibility study was followed to run the stabilization column at an optimum pressure and good thermodynamic efficiency. The optimized value of pressure and that usually applied in refinery were used to calculate heat flow of condenser and of reboiler. The results allowed us to highlight the effect of pressure on the separation of products. From an economic point of view, stabilization with optimal pressure may contribute to a decrease of costs related to the energy consumption of reboiler and decrease of CO2 emission and adjust the reflux ratio to a value of 3, and place the feed tray at the number tray 16 of the stabilization column increases the thermodynamic efficiency.

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