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Reduction of CO_2 Emission from Crude Oil Refining Process using Aspen Hysys Energy Analyser towards Environmental Sustainability

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ABSTRACT

Crude oil is a major source of energy across the globe due to its diverse product derivatives for various industries and applications. However, the high CO_2 emissions and energy requirements associated with its refining process threaten the goal of achieving carbon neutrality. The Crude Distillation Unit (CDU) has been identified as a major unit for CO_2 emissions. Therefore, it is important to investigate the composition of feedstock (blended crude oil samples) fed to the CDU as a possible alternative to reducing CO_2 emissions associated with refining. This study uses Aspen Hysys V12 with Aspen Energy Analyser to analyze different blended feedstock from six (6) different Nigerian crude oil; Brent, Bonga, Erha, Qua-Iboe, Usan, and Yoho. The result showed that Blend 1 had the highest CO_2 emission linked to the high conversion of paraffin and naphthene to yield the highest Naphtha yield of 27.12 % compared to other blends. Blend 1 also had the highest CO_2 emissions cost of \$13.92 million/hr compared to \$13.68 million/hr for Blend 7, with the lowest product yield. However, Blend 4 had the maximum heating energy requirement linked to its composition (mixtures of high medium and light crude) which require more reactions to maximize yield. The result revealed that individual crude's weight ratio in blended feedstock significantly increased Naphtha yield and affects CO_2 emissions. Thus, blended feedstock composition will affect product yield, energy consumption, and CO_2 emission due to the different compositions of individual crude. Therefore, to achieve the carbon neutrality goal, CO_2 emission from individual crude oil needs to be investigated, develop a new model for optimum blending with fewer emissions and the CO_2 emission cost should be added to blended feedstock price or individual crude cost to ensure a balance.

Keywords: Carbon neutrality, CO_2 emissions, High Naphtha yield, Aspen Hysys Energy Analyser, Crude Refining.

NONMENCLATURE

Abbreviations

CDU	Crude Distillation Unit
CI	Correlation Index
VDU	Vacuum Distillation Unit
HVGO	Heavy Vacuum Gas Oil
LVGO	Light Vacuum Gas Oil
LCGO	Light Coker Gas Oil
HCGO	Heavy Coker Gas Oil

Symbols

Kw= Watson factor

1. INTRODUCTION

The United Nations have set the year 2050 as the target for net carbon emissions to have a sustainable environment. However, due to increased energy demand across various industries and human activities, the global energy-related CO_2 emissions grew in 2022 by 0.9 % which is equivalent to 321 million tonnes [1]. A major contributor towards these CO_2 emissions is crude oil processing from various refineries. Recent research has estimated that by 2025, over 150 new refineries will be added to existing one across Asia, the Middle East, and Africa. This addition could emit up to 16.5 Gt of CO_2, if they run as usual without adopting new low-carbon emission measures [2]. Therefore, it is imperative to investigate the sources of such CO_2 emissions in the refining process. The refining process involves various unit operations and processing units. Crude Distillation units ((CDU): both vacuum and atmospheric distillation units), cracking unit and reforming have been identified as the major CO_2 emitters [3, 4]. With the CDU being the first unit operation, it is critical to investigate the

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feedstock fed to this unit, as its product would be feed to other units with their various recycle. Therefore, the CDU feedstock will be a determining factor towards decreasing the CO_2 emissions in the refining process.

The CDU feed is usually blended feedstock obtained from various crude oil types. Most refineries use blended feedstock to achieve optimum derivatives (high-value distillates), intending to maximise net revenue of cheaper crude oils and improve the oil refining profitability[5, 6]. Crude oil blending involves mixing two or more crude oils to obtain a feedstock (unique blend) that gives optimum desired product (light ends, gas oils), reduce transportation challenges and maximize profit [7]. Blending is achieved by maximising the crude composition of Naphthenic, Paraffinic and aromatic content characterised by the Watson factor (Kw as eqn. 1 shows), correlation index (CI as eqn. 2 shows) modified as SARA (saturates, aromatics, resins, asphaltenes), gravity and cost [8, 9]. It should be noted that many of the available types of crude oil (REBCO, Brent) come from blending (mixing) crude oil from various sources (different oil fields, countries, and continents) to obtain a resultant product of the declared quality. However, these blended derived feedstocks will yield CO_2 emissions during the refining, therefore it is important to investigate the associated CO_2 emissions for various blended feedstock.

Therefore, the objective of this study is to investigate the effect of blended feedstock on CO_2 emissions while maximizing product yield and minimizing energy consumption. Aspen Hysys (steady-state) and Aspen Hysys Energy Analyser will be used for the simulation and analysis beyond the CDU to the hydrocracker unit. These results are to assist researchers and process industry decide on different blended feedstock that would help achieve low CO_2 emissions toward the carbon neutrality goal.

2. MATERIAL AND METHODS

2.1 Crude oil selection

This study involved six diverse types of Nigerian crude oil from different oil fields. Their compositions, properties, product cuts to learn their suitability as feedstock for various blend feedstock were analysed using eqns. 1 and 2.

$$K_w = \frac{T_B^{1/3}}{SG} \tag{1}$$

$$CI = \frac{87{,}552}{T_B} + 473.3\,SG - 456.8 \tag{2}$$

Where, T_B: Average boiling point, °R, [ºF + 460].
SG: Specific gravity at 60°F.

2.2 Simulation and Modelling of Process

The process flow diagram for the main process units is shown in Fig. 1, while the various blend ratios used for the blended feedstock and individual crude properties are shown in Tables 1 and 2. Aspen HYSYS V12.1 with Peng-Robinson equation of state (eqn. 3) as the fluid property package was used to develop the model of the crude refining process from the Crude Distillation Unit (CDU), Vacuum Distillation Unit (VDU), Coke Fractionator and Hydrocracker to obtain the various yield Naphtha, Heavy Vacuum Gas Oil (HVGO), Light Vacuum Gas Oil (LVGO), Light Coker Gas Oil (LCGO) and Heavy Coker Gas Oil (HCGO).

$$P = \frac{R_g T}{v-b} - \frac{a(T)}{v(v+b)+b(v-b)} \tag{3}$$

Where P = Pressure, R_g = ideal Gas constant, T= Temperature, v =volume

$$a(T) = a(T_c)(1 + m(1 - T_r^{1/2}))^2, a(T_c) = \alpha \frac{R_g^2 T_c^2}{P_c},$$

$$b(T) = b(T_c) \quad , \quad b(T_c) = \beta \frac{R_g T_c}{P_c},$$

$$m = 0.37464 + 1.54226\omega + 0.26992\omega^2$$

Where, T_c and P_c are the critical temperature and pressure, T_r is the reduced temperature $T_r = T/T_c$, and ω is the acentric factor.

2.3 Energy and CO_2 Emission Analysis

Energy and CO_2 emission analysis was conducted with Aspen Energy Analyser with CO_2 emission cost factor of 0.22. The simplified assumption for total energy using pinch analysis is given in eqn. 4 and CO_2 emission is represented in eqn. 5.

$$Total\ \Delta H = (\textstyle\sum_i H\Delta_{hot} + \sum_i H\Delta_{cold})\ products\ + (\sum_i H\Delta_{hot} + \sum_i H\Delta_{cold})\ Units_i\ of\ operation \tag{4}$$

$$Total\ CO_2\ emissions = \textstyle\sum_i \left(CI_j\ x\ Process\ Units_i\right) \tag{5}$$

Where i is the number for various streams or unit.

$$\text{Cost of } \mathrm{CO_2} \text{ emission} = \text{Amount of } \mathrm{CO_2} \text{ emissions x \$ 0.22/kg} \tag{6}$$

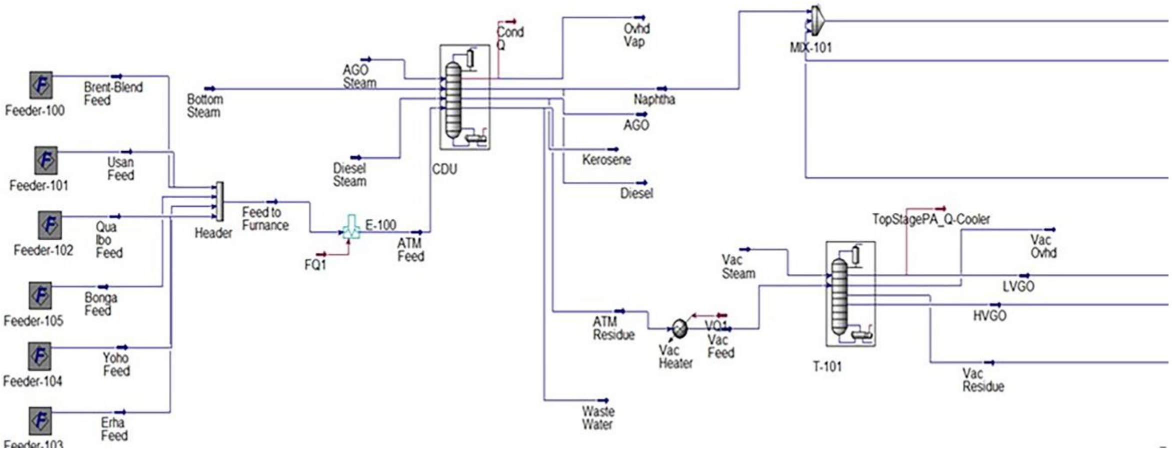

Fig. 1. Representation of the Atmospheric and Vacuum Crude Distillation flow diagram

Table 1: Crude Blend Ratios

Blend Sample	Bonga wt. %	Brent Blend wt. %	Erha wt. %	Qua-Iboe wt. %	Usan wt. %	Yoho wt. %
1	15	15	15	15	15	25
2	19	14	14	14	14	25
3	23	13	13	13	13	25
4	27	12	12	12	12	25
5	31	11	11	11	11	25
6	35	10	10	10	10	25
7	50	13.5	11.5	0	0	25

Table 2: Selected Nigerian Crude oil bulk properties

Properties	Bonga	Brent Blend	Erha	Qua-Iboe	Usan	Yoho
API Gravity	28.92	37.87	35.64	35.88	29.54	41.23
Watson Factor	11.29	11.68	11.54	11.59	11.24	11.63
Sulphur Content wt %	0.26	0.40	0.17	0.13	0.26	0.064
Paraffins	67.72	59.04	74.11	71.15	52.83	70.19
Naphthalene	28.77	40.47	21.27	27.79	46.09	26.83
Aromatics	3.51	0.49	4.62	1.05	1.07	2.67
Asphaltene	0.00	0.00	0.00	0.01	0.01	0.31
Classification	Medium, Paraffinic, Low in sulfur	Light, Paraffinic Low in sulfur	Light Paraffinic, Low in sulfur	Light Paraffinic Low in sulfur	Medium Paraffinic, Low in sulfur	Light Paraffinic, Low in sulfur
Cost per barrel ($)	79.67	85.12	84.78	82.66	79.67	86.56
Cost of Naphtha	$892/MT					

** data extarcted from various crude assay.

3. *RESULTS AND DISCUSSIONS*

3.1 Crude distribution yield

The distillate cut is an gives a reflection of the crude yield product distribution. Yoho had the highest distillate cut (Fig. 2a). This shows that its high API gravity (low specific gravity) and lowest sulfur content (impurities) among all samples as shown in Table 2 would improve its product derivatives. As previous report has shown that high API gravity (lower specific gravity) crudes yield high light distillates as they are easily cracked into volatile components which are beneficial for petrochemicals [10]. Also, an increase in the Naphthene and Aromatic ratios of individual crude increases the boiling point due to the viscosity of individual crude because of larger ring molecular structures (aromatics), which decreases the volatility and would require more energy for further cracking to obtain a valuable light product.

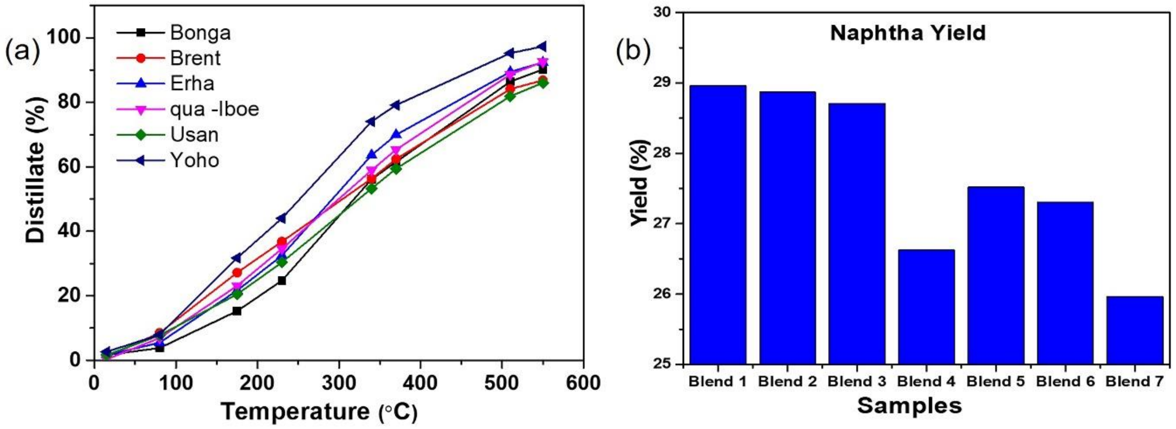

Fig. 2. (a) Distillate cut for individal crude oil, (b) Naphtha yield.

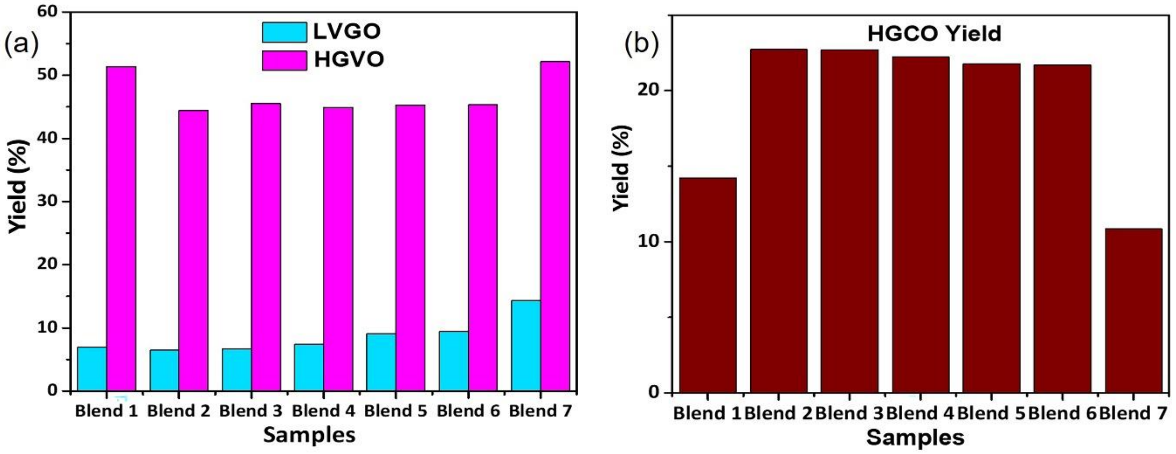

Fig. 3. (a) LVGO and HVGO yield, and (b) HGCO yield for various blend samples.

3.2 Derived product yield

To determine the amount of Naphtha yield from the various blended feedstock, which is the desire for industries, all Naphtha yield from various units were combined and depicted in Fig. 2(b). Blend 1 had the highest naphtha yield among the various samples. This observation is consistent with previous studies for high API gravity crude (high paraffinic content crudes) to give high product yield based on their volatility [11, 12]. Also, Blend 1, had the highest ratio of light crude oil mixed with heavy crude which would affect the viscosity of obtained blended feedstock. On the contrary, Blend 7 had the least Naphtha yield, linked to the weight ratio of 50 % contribution from medium crude which would yield a heavy blended feedstock. Further comparison of the yield from various blends clearly shows that individual crude composition influences product yield which justifies why refining industry blend feedstock to maximize yield.

The effect of blended feedstock on heavy products from the coker and cracker units are shown in Figs. 3(a and b). Blend 7 had the highest yield among the various samples in Fig.3(a). This clearly indicates that vacuum distillation favours condensation of large molecular compounds (aromatics) due to reduced boiling points. Furthermore, from Fig. 3(b), Blends 2, 3, 4 and 5 had high yield of HGCO linked the presence of high amount of aromatics and naphthene in their composition. It should be noted that these blended samples with high HGCO would require further cracking to obtain light end products. From Figs. 3(a and b), the nonlinear trend of product yield for other blended samples, shows that the weight ratio and composition of individual crude affects yield of blended feedstock, and would likely affect the overall energy requirement involved during the refining process.

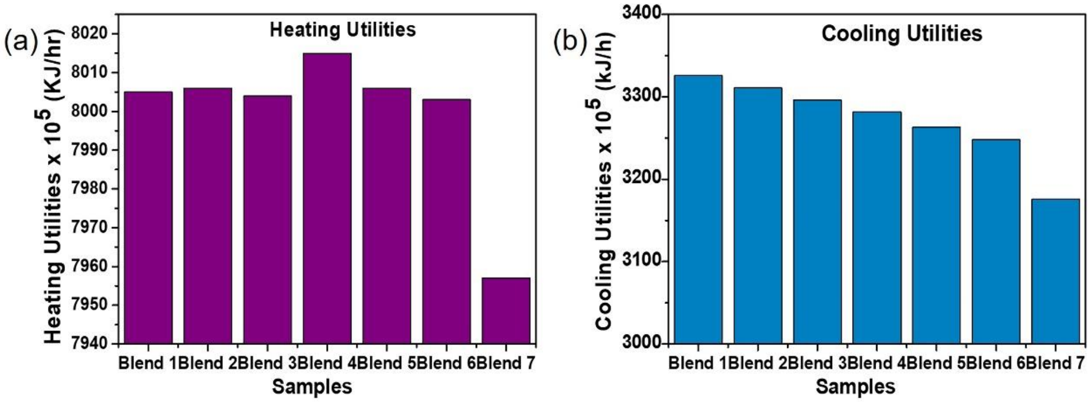

Fig. 4. Summary of Energy Analysis (a) heating utilities, and (b) cooling utilities.

3.3 Energy consumptions

To investigate the energy consumption for the process, Aspen Energy Analyser was implemented for the various utilities and material streams (hot and cold) using pinch analysis summarised in eqn. 4. From Fig. 4(a), Blend 4 had the highest heating utilities value of 8015 x 10^5 kJ/h linked to its composition distribution (Table 1) with a mixture of light and medium crudes. This blended feedstock sample would contain longer carbon chain due to its high Naphthene and aromatic content and would require more energy to break due to intermolecular forces reflected in its mixed yield of products Figs. 3 (a and b). The energy analysis for cooling utilities of various blended feedstock shown in Fig. 4(b) shows Blend 7 had the least value of 3176 x 10^5 kJ/h linked to its high composition of heavy crude (Table 1). This would result in low volatiles that do not require further cooling compared to other blends. This result shows that individual crude oil composition regarding its paraffinic, aromatics, and naphthenic content and weight ratio in blended feedstock would affect the energy requirement during refining due to the various cracking reactions and agrees with previous research [13]. These various energy requirements for each blend sample would likely affect the overall CO_2 emissions for the process.

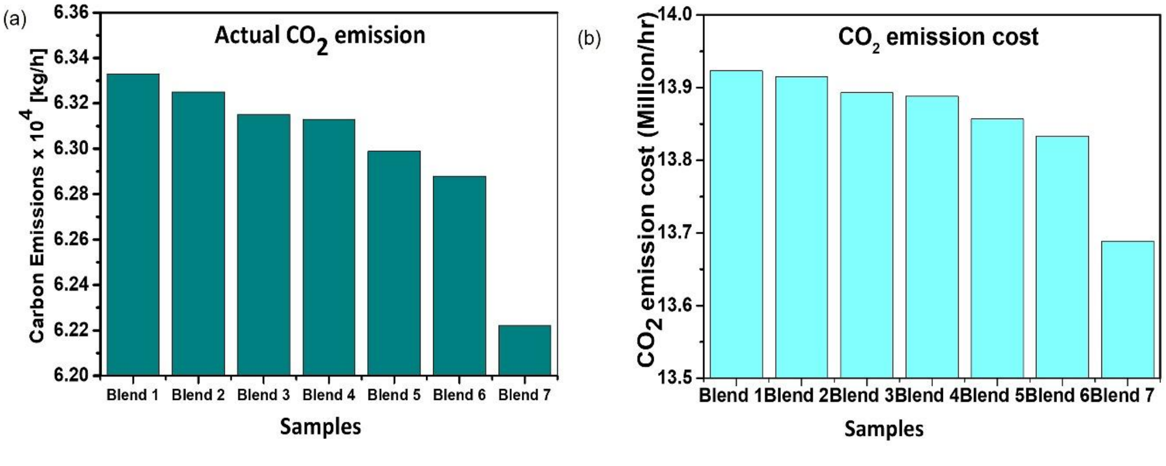

Fig. 5. (a) Actual CO_2 emissions, and (b) CO_2 emissions cost for various blend samples.

3.4 CO_2 emissions and CO_2 emiossion cost

To determine the amount of CO_2 emitted during the refining process, Aspen Economic Analysis was used with the summary shown in Fig. 5. From Fig. 5(a), Blend 1 had the highest actual CO_2 emission of 6.33 x 10^4 kg/h linked to the high conversion of Naphtha in section 3.2.1. High Naphtha yield resulted from the cracking of light-specific gravity blended feedstock. However, increase in cracking results to high CO_2 emission [15]. On the contrary, Blend 7 had the lowest CO_2 emissions of 6.22 x 10^4 kg/h, linked to less vaporization of carbon components in the blended feedstock, as it contains high aromatics in its composition as indicated in Table 1. Comparing Blend 1 and Blend 7, the CO_2 emission difference of 1030 Kg/h could become significant in the long run and increase environmental pollution. This result shows increased light crude feedstock composition will affect the CO_2 generated from blended feedstock during refining.

Further investigation of CO_2 emission cost for each blend was evaluated using eqn. 6 and shown in Fig. 5(b). Bend 1 had the highest CO_2 emissions cost of $13.92 million/hr compared to $13.68 million/hr for Blend 7, with the lowest product yield. Comparing Blend 1 with Blend 7, the difference of $ 0.24 million/hr is quite significant. This cost if factored into refining cost and would affect the operating cost. Therefore, to minimize the overall CO_2 emissions, the individual crude CO_2 emissions need to be investigated and considered before determining the weight ratio composition in blended feedstock which is the feed for the CDU.

4. CONCLUSIONS

This work has revealed that reducing CO_2 emissions from the crude refining process is possible if the blended feedstock fed to the CDU is optimized by varying the mixing ratio of individual crude whose paraffin, aromatics, and naphthene compositions are critical. The result analysis using Aspen Hysys with Aspen Energy Analyser showed that blended feedstock with a high ratio of light crude mixtures (high API gravity) significantly increases Naphtha yield but requires more heating energy and has high CO_2 emission. In contrast, blended feedstock with an increased ratio of medium crude had less energy requirement and CO_2 emissions but with a decrease in product yield, which will affect the net profit. Therefore, a CO_2 emission study for individual crude oil needs further investigation in order to develop a model for optimum blended feedstock with lower CO_2 emissions. Also, if CO_2 emission cost is pressed on for each crude oil, the processing cost would be surged by adding CO_2 emission cost. Hence this article sheds light on future crude oil selections for blended feedstock.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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