Process Simulation and Performance Models for Enhanced Modular Refinery Operations in Nigeria

Adeloye Olalekan Michael*, Akpa Jackson Gonurubon, Dagde Kenneth Kekpugile, and Ehirim Emmanuel Odionyegbuechua

***Abstract*—The study aimed at availability of petroleum products in Nigeria through the operation of enhanced modular refinery process due to inefficient conventional major refineries. The enhanced modular refinery converts or processes residue product from conventional modular refinery as feedstock to the hydrocracker reactor for viable and desired products such as liquefied petroleum gas, naphtha and diesel. Therefore, twenty Nigerian crude oil types were classified as sweet, light and medium crude oil, and these crude oil types were categorized based on their recovery volume at true boiling point of 370°C as Group A, Group B and Group C respectively. Thus, based on product output and equipment cost, a modular refinery with 29 trays was used in this study, as light and medium sweet crude oil types were simulated in a modular refinery of various column trays prior to the desired tray. A topping plant with a 30,000 barrel per day capacity and a modified topping plant with 29 trays respectively were used to process different types of Nigerian crude oil. using Aspen Hysys to evaluate their products yield and tray compositions. The modified modular refinery with hydrocracker yielded more valuable from the residue of conventional modular refinery with minimal bottom fraction. Performance models for hydrocracker reactor was developed based on the nature of reaction, kinetic parameters estimated and results compared with experimental data with minimum deviations. The developed performance models predicted feedstock conversion and product yield along the hydrocracker reactor's dimensionless length by solving a set of ordinary differential equation models. Thus, the hydrocracking process was simulated to evaluate the effects of catalyst effectiveness factor on feedstock conversion and products yield.**

***Index Terms*—Modular refinery, modified modular refinery, Nigerian crude oil types, hydrocracker, kinetic parameters, simulation, aspen Hysys**

I. Introduction

Petroleum refining includes processing of crude raw material in different physical and chemical processes, thereby yielding several products cuts. Thus, the processes of refining crude oil are chemical engineering based in addition to other suitable facilities present in crude oil refineries (oil refineries) to process petroleum into valuable products, which include liquefied petroleum gas, gasoline, kerosene, jet fuel, diesel oil and fuel oils [1, 2]. Petroleum refineries are huge industrial facilities that include several refining sections and other facilities (auxiliary), which include units for utility types of refinery with specific arrangement and factors such and storage tanks. Different as location of refinery, products of interest and economic considerations determines combination of refining processes [3, 4]. Thus, petroleum refineries refers to large-scale units that can process a few hundred thousand to a million barrels of petroleum every day. Due to its huge capacity, the refinery unit's activities are continually in contrast to batches, steady state, or almost steady state, for months to years. As a result, enhanced process control and process optimization are necessary [5, 6]. In petroleum refineries, the hydrocracker reactor is a catalytic reaction process used to transform crude oil residue with a higher boiling temperature, such as topping plant residue, into a lighter percentage of hydrocarbons like gasoline, liquefied petroleum gas, and diesel [7].

A modular refinery is described as a process plant that is entirely comprised of skid-mounted buildings, each of which contains a portion of the entire process unit and has components connected by piping to create an easily controllable operation [8]. A topping refinery is the most basic and cost-effective type of modular refinery. It is intended to produce liquefied petroleum gas, diesel, kerosene, naphtha, and its residue as a by-product [9]. Within 14 months of contract execution, a modular refinery may be built and operational, providing the host communities with vital fuels for transportation, power generation, water treatment, and job opportunities. [10, 11]. Large amounts of unprocessed product (residue) are produced by topping refineries, and local markets decide where they are installed. With capacities ranging from 1,000 to 30,000 barrels per day, the modular refinery process provides excellent quality control levels, economical use of space, and pre-delivery testing for effective process performance [5, 8]. With relatively cheap investment costs, speed, and construction time, topping refineries are quickly emerging as a practical, adaptable, and cost-effective option for petroleum producers, particularly where there is a pressing need to quickly supply local demand for crude oil products [12].

The major limitation of modular refinery operation can be ascribed to its fewer configurations with low production capacity and lower margins on products. The residue from modular refinery are usually transported through pipeline networks to conventional refinery for further processes since it contains more processing units. Thus, with the operating capacities of all conventional refineries in Nigeria between 15% and 25%, and inadequate provision of pipelines for crude oil and products delivery [13], the issue of topping plant bottom product (residue) treatment has been of great concern for operators, researchers and professionals in developing countries like Nigeria. Some of the limitations associated with previous studies on modular refinery

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operations in Nigeria include crude oil classification and characterization are carried out on few types of Nigeria crude oil [14–20], studies have been carried out on operational feasibility of modular refinery (Topping plant) operation in Nigeria with no reference to its bottom product (residue) processing or treatment [9, 11, 12, 16, 21–24]. Therefore, researchers and operators proposed transportation of bottom product (residue) via pipeline or tanker networks to conventional main refinery for additional processing, but this is impossible in Nigeria currently as conventional major refineries are not functional (operational efficiency less than 20%) [13, 25].

Thus, the aim of this study is to enhance production of petroleum products from modular refinery (topping plant) processes in Nigeria via the analysis and classification of twenty Nigerian crude oil types by using crude assay data in Aspen Hysys software to assess the cut fraction of their products, recovery volume, compositions, properties and products recovery temperature range, simulate the twenty Nigerian crude oil types with modular refinery (Topping plant) of different column trays (25, 29, 35, 40, and 48) using Aspen Hysys, therefore suggesting a number of column trays based on product yield and equipment cost for this investigation, simulate twenty Nigeria crude oil types with Topping Plant of proposed column trays to determine products yield on each tray of the column, propose a modified modular refinery (topping plant with hydrocracker) based on desired column trays for processing twenty Nigerian crude oil types, develop models for hydrocracking reactor based on the type of reaction taking place using lumping scheme, kinetic parameter estimate of the process using regression analysis with MatLab software and simulate the effect of parameters on the overall efficiency, conversion and performance of hydrocracking reactor.

II. Materials and Method

The following materials and method were applied in carrying out this research study

A. Materials

Twenty different types of Nigerian crude oil, residue, modular refinery, hydrocracker reactor, operating data, Aspen Hysys and MatLab ODE45 Solver etc were used in this research study

B. Methods

The following methods are applied in carrying out this study.

1) Crude oil analysis and classification

The initial step in this research study is the analysis of twenty distinct types of Nigerian crude oil from diverse oil fields to determine their viability as feedstock for modular refineries (topping plants) based on their compositions, characteristics, and product cuts. Crude oil analysis refers to compilation of crude oil properties and composition data that reveals pertinent information on crude oil suitability for a specific refinery and estimation of the desired product fractions and quality. API gravity, total sulfur (%wt), pour point (°C), viscosity @ 20°C (cSt), viscosity @ 40°C (cSt), nickel (ppm), vanadium (ppm), total nitrogen (ppm), total acid number (mgKOH/g), distillation data, and Watson characterisation factor are the key specifications of crude oil test. As a result, the grade of the crude oil type is determined by evaluating and using these factors (light, medium, heavy, sweet and sour crude). In order to estimate the weight percentage of pure crude components, the products recovery temperature, and the correct boiling point, the crude oil test data were also applied as input into the Aspen Hysyss program.

2) Modular refinery (topping plant) process

Traditional modular refineries referred as topping plant with the crude distillation unit (CDU) as its main unit and other accessory units such as mixer, heater, heat exchanger, desalter, flash separator, condenser and reboiler as shown in Fig. 1. Simulation processes of Nigeria various types of crude oil with topping plants at different column trays were carried out using Aspen Hysys to determine their products (Off gas, Naphtha, Kerosene, diesel, Atmospheric gas oil and Residue) composition and each tray composition, thereby ascertaining the modular refinery's operational procedure in Nigeria.

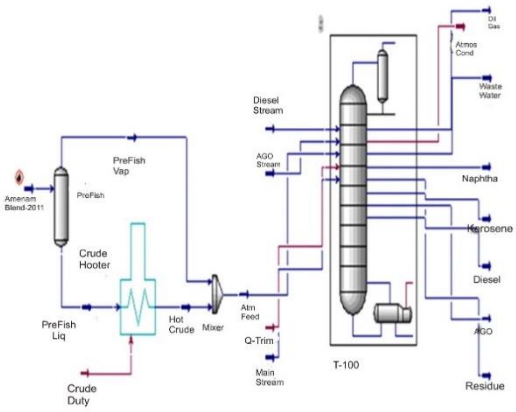

Fig. 1. 30,000bpd capacity modular (topping plant) refinery.

Fig. 1 showed a traditional modular refinery (Topping plant) for processing 30,000BPD crude oil via Aspen Hysys. The topping plant was operated at different column trays (25, 29, 35, 40, and 48) in the unit for crude distillation with the operating conditions of the atmospheric distillation column of the Port Harcourt refinery applied in the operation of the topping plant. These column trays were chosen to study the operational effects of trays on products yield with forty-eight maximum column trays in tandem with the refinery's crude distillation facility in Port Harcourt. Thus, equipments cost were evaluated at different column trays in proposing a column tray for this research process. Hence, this study simulated twenty Nigerian crude oil types in a topping plant of twenty-nine column trays to yield product components (Off gas, Naphtha, Kerosene, diesel, Atmospheric gas oil and Residue).

3) Modified modular refinery simulation

Twenty different types of Nigerian crude oil are processed using the modified topping plant with twenty-nine column trays after crude oil analysis and classification, and their product yields compared with simulation yield of conventional modular refinery with same column trays. The modified modular refinery fed the hydrocracker unit attached to its stripping section with residue from the standard modular refinery as feedstock in order to recover more valuable products (liquefied petroleum gas, naphtha and diesel) as depicted in Fig. 2. The traditional modular refinery's crude distillation unit stripping section is modified via connection with a hydrocracker reactor, and hydrogen is supplied via steam methane reforming operation. The bottom product from Fig. 1 called residue is hydrocracked to yield light valuable products such as light ends (liquefied petroleum gas), naphtha and diesel using Aspen Hysys software as shown in Fig. 2. Thus, the light ends product (liquefied petroleum gas) is cooled and stored at temperature below −42°C (−43.6°F).

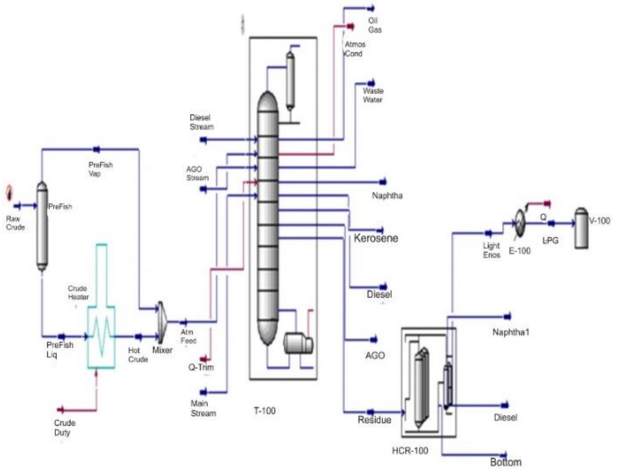

Fig. 2. 30,000bpd capacity modified modular refinery.

4) *Development of hydrocracking reactor model equations*

To forecast its performance, the hydrocracker reactor of the upgraded modular refinery is modeled. through the determination of reaction taking place, their rate equations and kinetics of the process using five lump reaction scheme.

a) Assumptions

The following assumptions are applied in developing performance model equations that predicts the yield of hydrocracked products in a packed bed catalytic hydrocracker reactor.

1. There is an extra supply of hydrogen gas and the rate of hydrocracking is independent of hydrogen concentrations.
2. The reaction rate is independent of the partial pressure of hydrogen gas.
3. All products and feedstock are in the liquid phase, and the hydrogen feed is pure.
4. The hydrocracking reaction process involves first-order reactions.

b) Nature of reaction in hydrocracker reactor

The nature of the reaction occurring in the hydrocracker reactor was determined from its voidage value analysis as shown by Adeloye [26].

$$\varepsilon = \frac{V_{XA=1} - V_{XA=0}}{V_{XA=0}} \tag{1}$$

c) Kinetics of the reaction

A kinetic model equation is an important scheme for design adequacy and solution of chemical operations [27]. The reaction kinetics therefore refers to the equation of rate and rate constant of the reaction occurring in the hydrocracker reactor. Thus in this study, five lumps system which consist of the input (traditional modular refinery waste) and hydrocracker unit output such as liquefied petroleum gas, naphtha, diesel and bottom are used in the design model of the reactor. Fig. 3 depicts the reaction pathway for the hydrocracking process for the five lumps scheme.

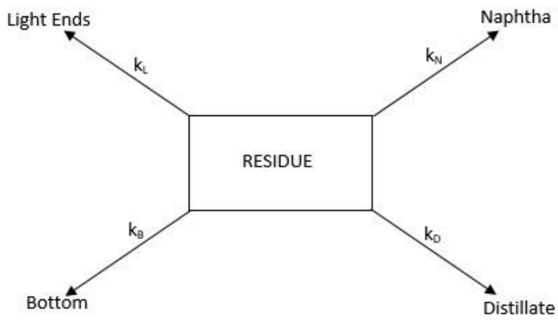

Fig. 3. Five lumps scheme for hydrocracker.

i. Feedstock depletion rate equation

The reaction rate equation for converting conventional modular refinery residue (feedstock) into more valuable products via a hydrocracker reactor based on mass fraction is expressed as

$$-r_j = -\eta \sum_{i=1}^{4} k_i y_i \tag{2}$$

ii. Product stream rate equation

The general reaction rate equation representing the product streams (liquefied petroleum gas, naphtha, diesel and bottom) in terms of mass fraction is expressed as

$$-r_i = -\eta k_i y_i \tag{3}$$

The reaction rate constants in the rate equations are also evaluated by using Arrhenius equation. Thus, the general expression for evaluating reaction rate constants is expressed as

$$k_i = k_{i0} exp\left(\frac{-E_i}{RT}\right) \tag{4}$$

d) Performance model equations for hydrocracking reactor

A schematic flow diagram of catalytic hydrocracking (packed bed) reactor is shown below:

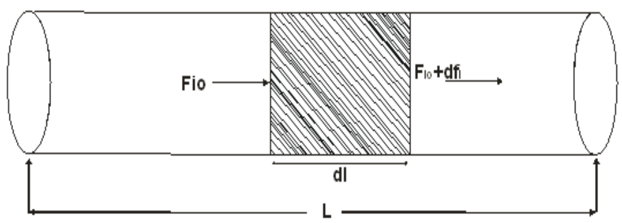

Fig. 4. Packed bed catalytic hydrocracker reactor.

The general material balance equation is represented as following the use of the law of conservation of mass as:

$$\begin{aligned} &Rate\ of\ Accumulation\ of\ Material\ into\ the\ Reactor \\ &= Rate\ of\ inflow\ into\ the\ reactor \\ &- Rate\ of\ outflow\ from\ the\ rector \\ &\pm Rate\ of\ production\ or\ depletion\ within\ the \\ &reactor\ due\ to\ chemical\ reaction \end{aligned} \tag{5}$$

At steady state, the material balance equation expressing the depletion of feedstock with respect to hydrocracker reactor dimensionless length is described as

$$\frac{dy_j}{dl_d} = \tau\varepsilon\eta \sum_{i=1}^{4} k_i y_i \tag{6}$$

Similarly, the material balance equation for the yield of products in the hydrocracker reactor at steady state is expressed as

$$\frac{dy_i}{dl_d} = \tau\varepsilon\eta k_i y_i \tag{7}$$

e) Estimation of kinetic parameters

The rate constants used in solving the generated model equations for the hydrocracker reactor are important in evaluating the kinetic parameters, which include pre-exponential factors and activation energies. These parameters are estimated in this study by applying the single point regression analysis and MatLab software that solves complex non-linear expressions, and the estimated values are considered to be the best values among plant data, literature data, and experimental data in solving developed model equations. Thus, these kinetic parameters are estimated by minimizing the objective function, *S*; subject to the constraint $y_{i,0,}$ that gives the estimated values of $y_{\iota,\text{est}}$ as:

$$S = \sum_{i=1}^{m} (y_{\text{iPlant}} - y_{\text{i,Cal}})^2 \tag{8}$$

Subject to (Constraint) models $y_{\text{i,lit}}$ such that $y_{\text{i,lit}} > 0$ and the flowchart for estimation of kinetic parameters is shown in Fig. 5.

III. PROCESS OPERATING PARAMETERS

The process parameters (plant and literature data) and the composition of catalyst applied in this study for the catalytic hydrocracker reactor are highlighted in Tables I and II respectively.

TABLE I: CATALYST SPECIFICATIONS FOR HYDROCRACKER

Properties	Value
Shape	Spherical
Mesh	10–20
Bulk Density	654kg/m^3
Density (Solid)	2500Kg/m^3

Source: Adeloye [26].

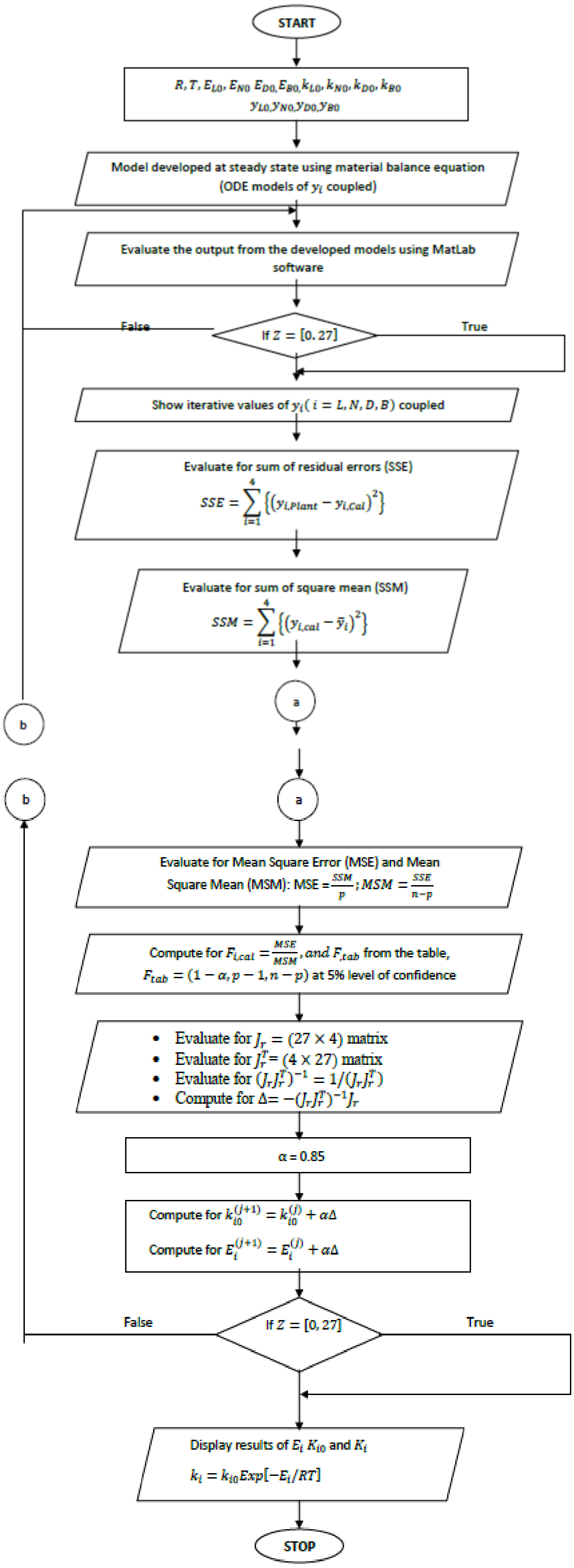

Fig. 5. Flow chart for estimation of kinetic parameters of hydrocracker.

TABLE II: COMPOSITIONS OF CATALYST

Components	Value (Wt%)
SiO_2	55.39
Al_2O_3	9.27
WO_3	24.53
NiO	3.55
CaO	0.46
Fe_2O_3	Trace

Source: Adeloye [26].

The properties and operating parameters of the hydrocracker reactor are shown in Table III, while Table IV depicted the experimental kinetic parameters values as described by Sadighi [29].

TABLE III: HYDROCRACKER REACTOR OPERATING PARAMETERS

Parameters	Value	Unit
Reactor Diameter	4.734	M
Diameter to Length Ratio	1:11	
Feed Flow Rate	298.6193	kgmol/hr
Pressure	150-200 (183)	bar
Temperature	300-425	ºC
Porosity of Catalyst Bed	(380ºC)	-
Bulk Density of Bed	0.345-0.55	kg/m^3
Diameter of Particle	654	m
	2×10^{-3}	

Sources: Adeloye [26], Farag *et al*. [28], Sadighi [29].

TABLE IV: FIVE LUMPS EXPERIMENTAL KINETIC PARAMETERS

Parameters	Light Ends	Naphtha	Distillate	Bottom
Activation Energy (cal/mol)	5,610	41,340	49,630	23,510
Frequency Factor (hr^{-1})	52.84	9.3×10^8	2.34×10^{16}	2.25×10^8

Source: Sadighi [29].

IV. RESULTS AND DISCUSSION

These findings from the research study are discussed.

A. *Analysis and Classification of Crude Oil*

The results of the crude oil analysis and classifications of the twenty Nigerian crude oil types based on their API values, sulphur content, Watson characterization factor and recovery volume of crude at operating temperature of 370ºC. The 20 different types of crude oil in Nigeria were classified, and they were divided into light crude (API value over 38) and medium crude (API value between 22 and 38), but there was no heavy crude (API value below 22). These forms of crude oil are sweet crude as well since they often have sulphur contents below 0.5 weight percent (sour crude oil has sulphur contents above 0.5 weight percent), and Watson characterization factors of the twenty crude oil types ranges between 11.26 and 12, which shows that the twenty crude oil types are nor extremely naphthenic nor highly paraffinic crude. The results of these analysis and classification are in agreement with previous study by Adeloye *et al*. [3] as shown in Table V. Additionally, the twenty Nigerian crude oil types were divided into three groups based on the recovery volume of each type of crude oil at operating temperature of 370ºC, with Group A Nigerian crude oil types producing high recovery volumes of eighty percent (80%) and above and relatively low sulphur contents as shown in Fig. 6. These crude oil types are suitable for conventional modular refinery operations in Nigeria. Also, Nigerian crude oil types with recovery volume of seventy percent (70%) and above but lower than 80% are highlighted in Fig. 7 as Group B, and Fig. 8 proposes that Nigerian crude oil types with recovery volumes less than seventy (70%) are classified as Group C. Therefore, Groups B and C of Nigerian crude oil types contain a high percentage of residue (above 20%) and are suitable for modular refineries (Topping plant), but the high residual percentage volume is a significant constraint or restriction, and there is a need to process the residue to more valuable products. Therefore, modified modular (topping plant) refineries are more suited for processing Groups B and C Nigerian crude oil types.

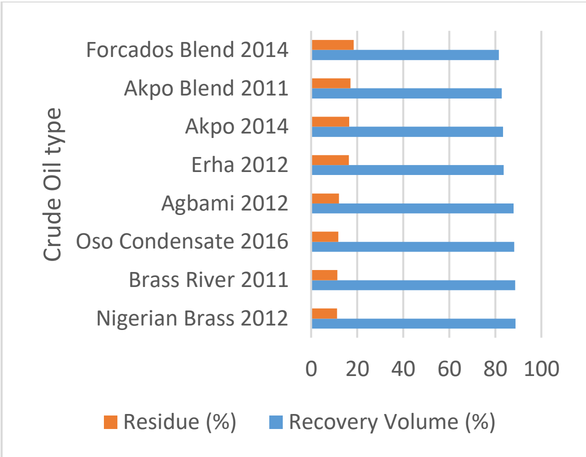

Fig. 6. Group A Nigerian crude oil classification.

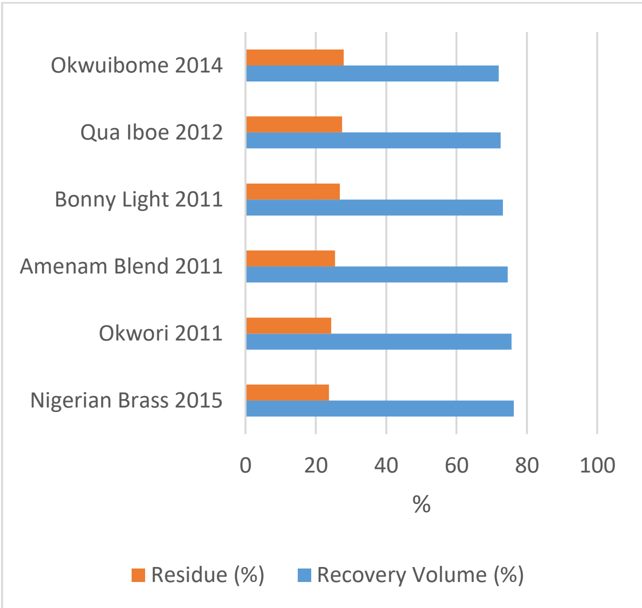

Fig. 7. Group B Nigerian crude oil classification.

TABLE V: CLASSIFICATION OF NIGERIAN CRUDE OIL TYPES

S/N	Crude Oil Type	API Value	Sulphur Content (Wt%)	Recommendation
1	Agbami 2012	48.66	0.043	Light Sweet Crude
2	Akpo Blend 2011	46.70	0.069	Light Sweet Crude
3	Akpo 2014	46.58	0.07	Light Sweet Crude
4	Amenam Blend 2011	39.81	0.10	Light Sweet Crude
5	Nigeria Brass 2012	40.62	0.108	Light Sweet Crude
6	Oso Condensate 2016	48.78	0.031	Light Sweet Crude
7	Bonny Light 2011	34.50	0.146	Medium Sweet Crude
8	Brass River 2011	37.01	0.099	Medium Sweet Crude
9	Erha 2012	36.11	0.157	Medium Sweet Crude
10	Forcados Blend 2014	32.29	0.220	Medium Sweet Crude
11	Nigeria Brass 2015	37.10	0.120	Medium Sweet Crude
12	Okwori 2011	36.04	0.111	Medium Sweet Crude
13	Okwuibome 2014	33.41	0.134	Medium Sweet Crude
14	Qua Iboe 2012	36.23	0.117	Medium Sweet Crude
15	Bonga 2012	31.06	0.238	Medium Sweet Crude
16.	Okoro 2012	23.54	0.206	Medium Sweet Crude
17	Nigeria Forcados 2012	30.65	0.187	Medium Sweet Crude
18	Bonga 2014	30.89	0.225	Medium Sweet Crude
19	Usan 2013	31.08	0.228	Medium Sweet Crude
20	Usan 2015	29.76	0.258	Medium Sweet Crude

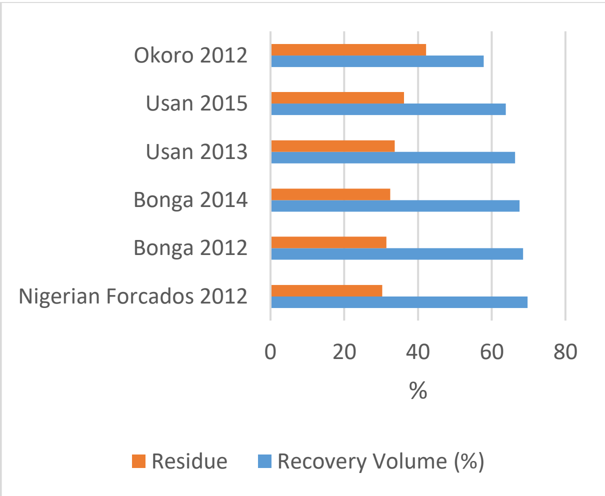

Fig. 8. Group C Nigerian crude oil classification.

B. Simulation of the Topping Plant at Various Tray Numbers

To evaluate the impact of different column trays on overall product production and equipment costs, light sweet (Akpo Blend 2011 with an API of 46.70) and medium sweet (Okoro 2012 with an API of 23.54) crude oil types were simulated in a standard modular refinery shown in Fig. 1. The products yield of Akpo 2011 and Okoro 2012 at different column trays are shown in Tables VI and VII respectively.

TABLE VI: PRODUCT YIELD OF THE 2011 AKPO BLEND AT VARIOUS COLUMN TRAYS

Products Yield (Kgmol/hr)	Crude Distillation Column at Different Tray Numbers				
	25	29	35	40	48
Off Gas	1.02×10^{-5}	3×10^{-5}	2.99×10^{-5}	3.08×10^{-5}	3.07×10^{-5}
Naphtha	320.59	321.95	322.01	322.01	322.81
Kerosene	133.60	135.86	135.96	135.96	136.01
Diesel	221.18	227.15	227.15	228.00	228.40
Gas Oil	60.33	62.25	63.18	63.24	63.30
Residue	166.10	154.80	153.70	152.60	151.40

TABLE VII: OKORO 2012 PRODUCT YIELD AT DIFFERENT COLUMN TRAYS

Products Yield (Kgmol/hr)	Crude Distillation Column at Different Tray Numbers				
	25	29	35	40	48
Off Gas	2.27×10^{-5}	2.1×10^{-5}	3.84×10^{-4}	3.79×10^{-4}	3.79×10^{-4}
Naphtha	132.76	139.23	139.42	140.31	141.18
Kerosene	94.79	108.21	109.11	109.21	110.42
Diesel	180.86	200.48	201.88	202.02	202.48
Gas Oil	88.66	55.11	56.81	56.91	57.01
Residue	404.03	398.96	394.87	392.65	390.89

The size (height and diameter) and cost of the crude distillation unit are dependent on the column trays or plates, hence cost analyses of the topping plant equipment were also performed using Aspen Hysys at various column trays. Table VIII displays the equipment costs for different column trays for light sweet crude (Akpo Blend 2011) and medium sweet crude (Okoro 2012). As a result, equipment costs at a certain column tray are greater in Okoro 2012 than in Akpo Blend 2011 due to Okoro 2012's increased heat duty costs. Crude distillation column with twenty-nine number of trays was suggested and used in this research study based on product yield and equipment cost analysis.

TABLE VIII: EQUIPMENT COST FOR DIFFERENT TRAY COLUMNS

Column Tray	Equipments Cost (US$)	
	Akpo Blend 2011	Okoro 2012
25	1,555,900.00	1,607,100.00
29	1,632,500.00	1,658,200.00
35	1,787,500.00	1,798,400.00
40	1,865,200.00	1,886,500.00-
48	1,993,700.00	2,061,500.00

C. Proposed Conventional Modular Refinery

Twenty different types of crude oil from Nigeria were simulated in a modular refinery with a 30,000 bpd capacity, consisting of twenty-nine column trays or plates in the crude distillation unit, in order to ascertain the compositions or yields of each column tray. Thus, it is possible to deduce the maximum and lowest product yield or composition of each type of crude oil at the corresponding tray number. Figs. 9 and 10 respectively depict the product tray compositions for Akpo 2011 and Okoro 2012.

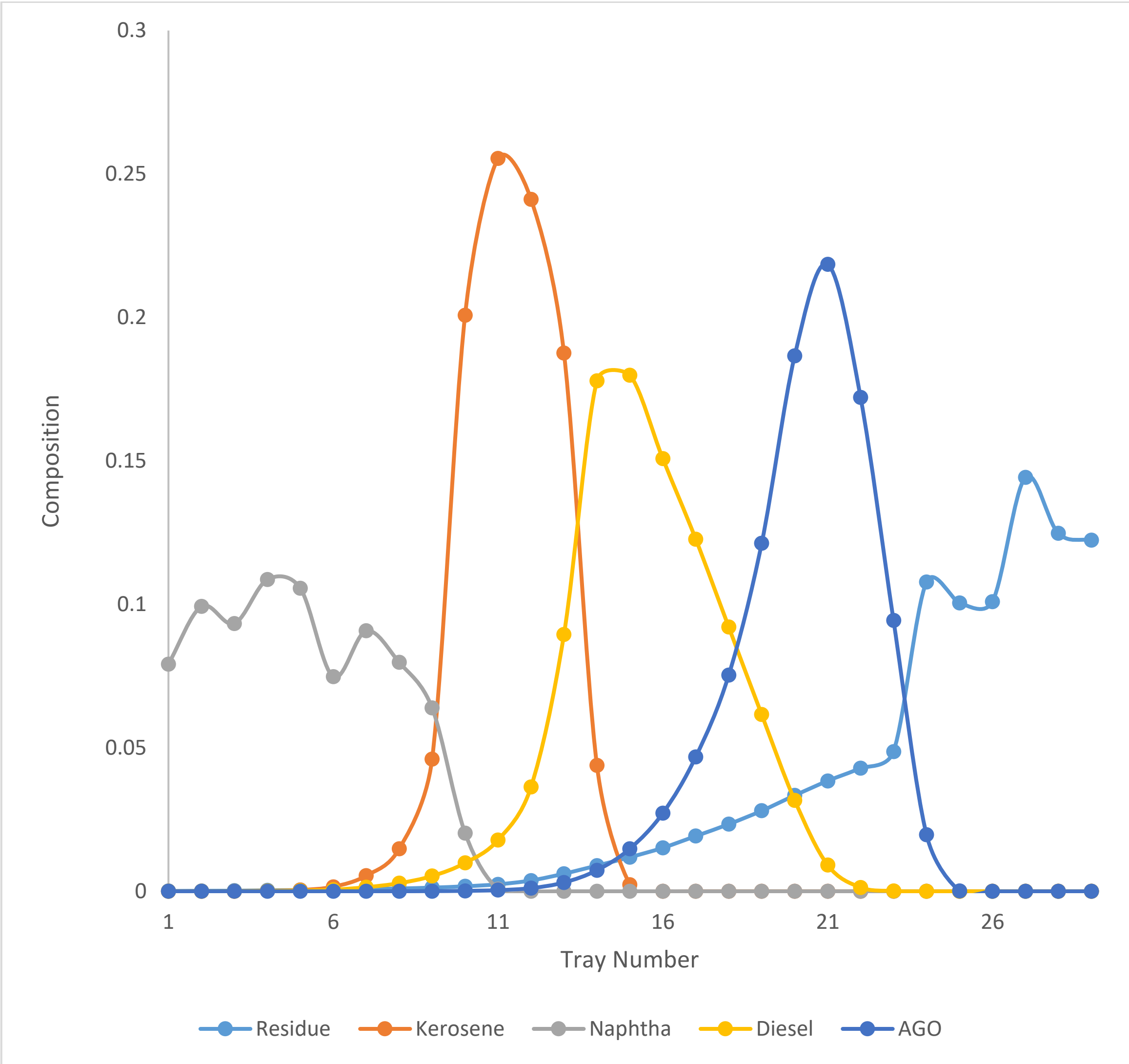

Fig. 9. Products tray compositions of Akpo blend 2011.

Fig. 9 depicted the plot of tray composition against tray number for Akpo blend 2011, which shows maximum and minimum composition of products at a respective tray number as naphtha (0.108671% and 2.62×10^{-93}%) at trays 4 and 27, kerosene (0.2554216% and 3.6×10^{-64}%) at trays 11 and 29, diesel (0.179907% and 7.52×10^{-28}%) at trays 15 and 29, atmospheric gas oil (0.218483% and 1.72×10^{-14}%) at trays 21 and 29 and residue (0.144269% and 1.15×10^{-4}%) at trays 27 and 1. Also, it can be deduced from Fig. 9 that naphtha (0.123%), kerosene (0.272%), diesel (0.192%), atmospheric gas oil (0.217%) and residue (0.154%) have their maximum plate compositions at column trays 5, 12, 15, 21 and 27 respectively and minimum plate compositions corresponding to the respective products naphtha (3.66×10^{-45}%), kerosene (9.61×10^{-31}%), diesel (1.43×10^{-26}%), atmospheric gas oil (1.24×10^{-12}%) and residue (8.6×10^{-5}%) at trays 25, 27, 29, 29 and 1 respectively. Also, it can be deduced from Fig. 10 that naphtha (0.123%), kerosene (0.272%), diesel (0.192%), atmospheric gas oil (0.217%) and residue (0.154%) has their maximum plate compositions at trays 5, 12, 15, 21, and 27 respectively. The minimum plate compositions corresponding to the respective products naphtha (3.66×10^{-45}%), kerosene (9.61×10^{-31}%), diesel (1.43×10^{-26}%), atmospheric gas oil (1.24×10^{-12}%) and residue (8.6×10^{-5}%) at trays 25, 27, 29, 29 and 1.

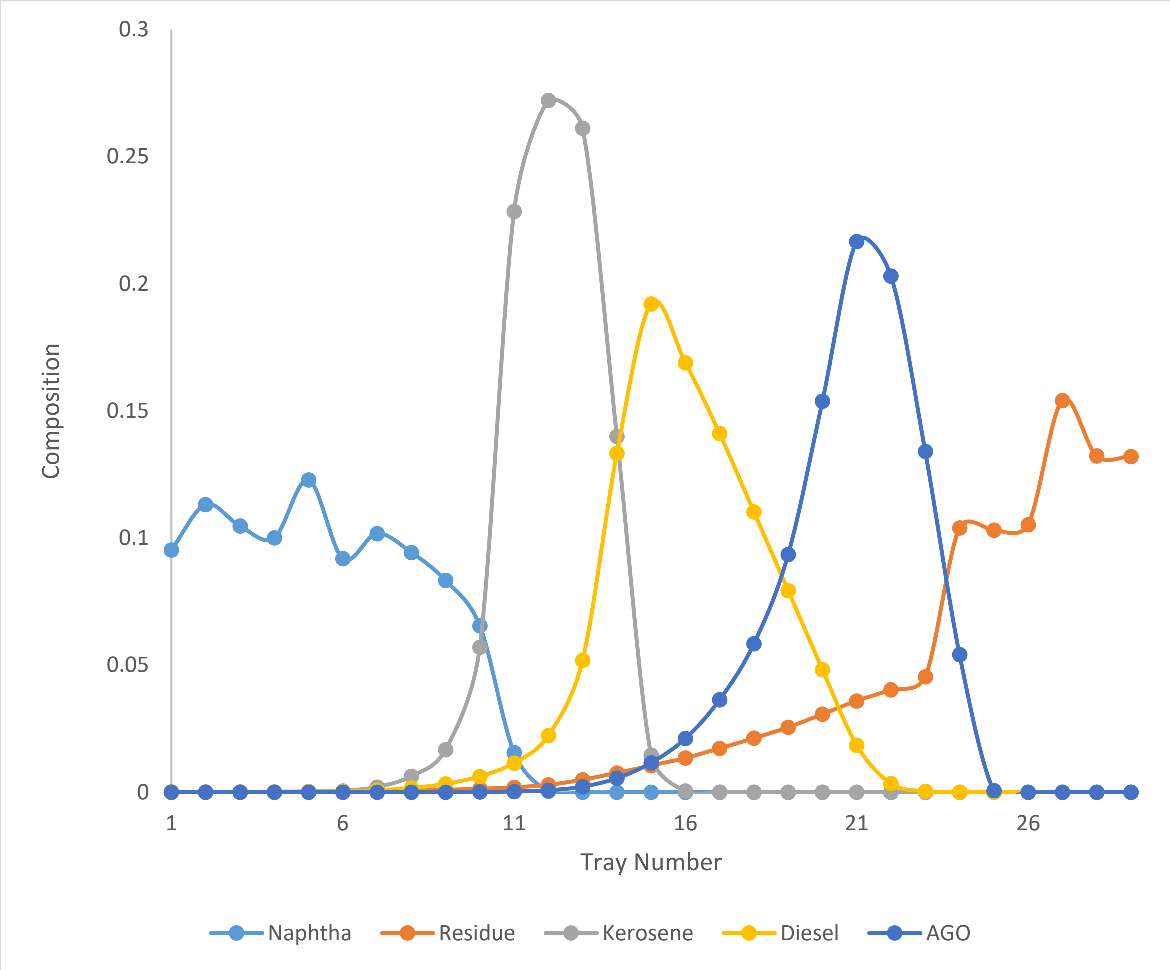

Fig. 10. Products tray compositions of Okoro 2012.

D. Proposed Modified Modular Refinery

The proposed modified conventional topping refinery depicted in Fig. 2 was applied in simulating classified Nigerian crude oil types. The residual fraction from the stripping column of the crude distillation unit of conventional modular refinery were processed in the hydrocracker reactor to yield more light valuable products like light ends (liquefied petroleum gas), naphtha and diesel, thereby improving or enhancing petroleum products yield from the topping plant operation. Thus, the light ends (mainly propane and butane) are cooled and used as liquefied petroleum gas, naphtha as feedstock for petrochemical industry, diesel for power generation and as vehicular fuel, while the bottom product is recycled with fresh residue from topping plant process. The residual percentage compositions of 30,000 bpd proposed conventional modular and modified modular refinery for twenty Nigerian crude oil types are shown in Fig. 11.

Thus, Fig. 11 demonstrated that the proposed modified modular refinery's residual percentages are incredibly low when compared to the conventional modular refinery, attesting to the fact that the residual issue related to conventional modular refinery operations in Nigeria was largely resolved by the proposed modified modular refinery.

E. Nature of Hydrocracker Reactor

The nature of hydrocracker reactor is determined by evaluating the reaction taking place in the reactor through the application of Eq. (1). The evaluation analysis of the nature of reaction occurring in the hydrocracker reactor yielded zero value, which shows that the hydrocracker operation is isothermal and this is in accordance with other researches or studies on hydrocracker by Adeloye [26], USEIA [30] and Matos and Gurirardello [31] respectively. his deduction was applied in developing performance model equations for the hydrocracker reactor.

F. Kinetic Parameters and Performance Models Validation

The estimated process kinetic parameters that include pre-exponential constants and activation energies of the reaction paths were compared with plant data (experimental data) in checking the accuracy of estimated values. Therefore, Tables IX and X illustrate the comparison of plant data (experimental data), calculated findings of pre-exponential factors, and activation energies respectively.

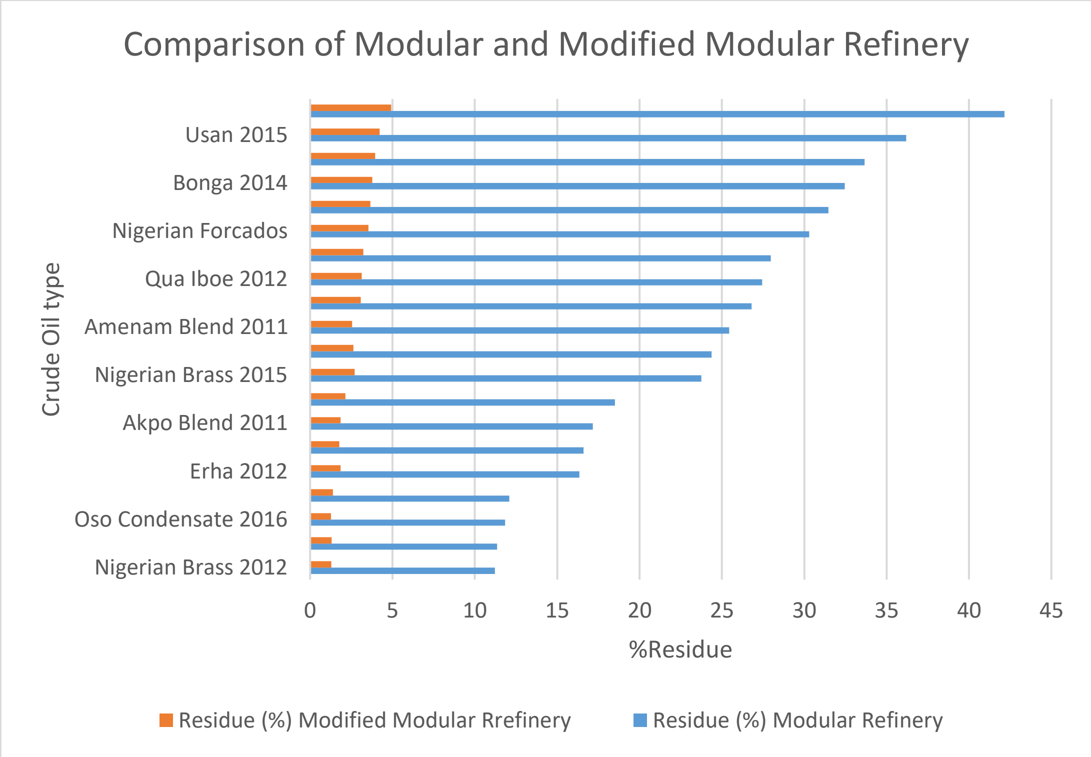

Fig. 11. Percentage of the modular and modified MODULAR refinery's residual product.

TABLE IX: COMPARISON OF ESTIMATED AND EXPERIMENTAL DATA OF PRE-EXPONENTIAL FACTORS (hr^{-1})

Parameters(k_{i0})	Experimental Data	Estimated Data	Deviation (%)
Light Ends	52.84	51.9547	1.6754
Naphtha	9.3×10^{8}	9.299×10^{8}	1.08×10^{-3}
Diesel	2.34×10^{16}	2.339×10^{16}	4.27×10^{-3}
Bottom	2.25×10^{8}	2.25×10^{8}	0.0000

Table IX showed deviations or absolute error values between estimated and experimental pre-exponential factors to be 1% maximum percentage deviation for light ends, while other deviations for pre-exponential factors are extremely below 1%. Also, the comparison of estimated and experimental activation energies shown in Table X yielded absolute error value of 2.2% maximum for distillate activation energy while other products deviations are quite negligible, which testifies to the accuracy or correctness of the estimated activation energies.

TABLE X: COMPARISON OF ESTIMATED AND EXPERIMENTAL DATA OF ACTIVATION ENERGIES $(Kcal/mol)$

Parameters(E_i)	Experimental	Estimated	Deviation
Light Ends	5.61	5.6151	0.0909
Naphtha	41.34	41.3388	0.0029
Diesel	49.63	48.5074	2.2619
Bottom	23.51	23.5293	0.0820

Furthermore as shown in Table XI, the comparison of the hydrocracker reactor's product yield using Okoro 2012 residue from Aspen Hysys as feedstock and the developed models revealed minimal error or deviation values, demonstrating the applicability of model equations for simulating hydrocracker reactors.

TABLE XI: COMPARISON OF THE HYDROCRACKER YIELD BASED ON ASPEN HYSYS AND DEVELOPED MODELS

Parameters	Aspen Hysys	Model Yield	Deviation
Light Ends (Gases)	0.3435	0.3588	4.4542
Naphtha	0.1081	0.1135	4.9954
Diesel	0.4316	0.4403	2.0158
Bottom	0.1168	0.0874	25.1712

Thus, it can be deduced from Table XI that there is improved percentage yields of desired or valuable products (liquefied petroleum gas, naphtha and diesel) with relatively low bottom product yield from the simulated performance model equations in comparison to Aspen Hysys simulation. This is owing to the effectiveness of estimated kinetic parameters of the process.

G. *Simulation of Models*

The developed model equations were used to simulate the impacts of catalyst effectiveness factors on feedstock (traditional modular refinery residue) and products yield of the hydrocracker reactor based on the validation of the estimated kinetic parameters and its performance models.

1) *Variation of feedstock with reactor dimensionless length*

Fig. 12 illustrates the results of the study on the conversion or depletion of feedstock (residue from the topping plant) in the hydrocracker reactor along the reactor's dimensionless length. As a result, Fig. 6 demonstrated a decline in feedstock levels, confirming that feedstock (or reactant) consumption was constant across all values of the catalyst effectiveness factor. With the feedstock approaching zero at a reactor's dimensionless length of 0.3846, the depletion of feedstock occurs more quickly with effectiveness factors of 80% and 90%, respectively. Additionally, the feedstock conversion rate increases as the catalyst effectiveness factor rises and was lowest at a catalyst effectiveness factor of 10%. As a result, with high catalyst effectiveness factors, catalyst activity causes the conversion of feedstock in the hydrocracker reactor to occur more quickly.

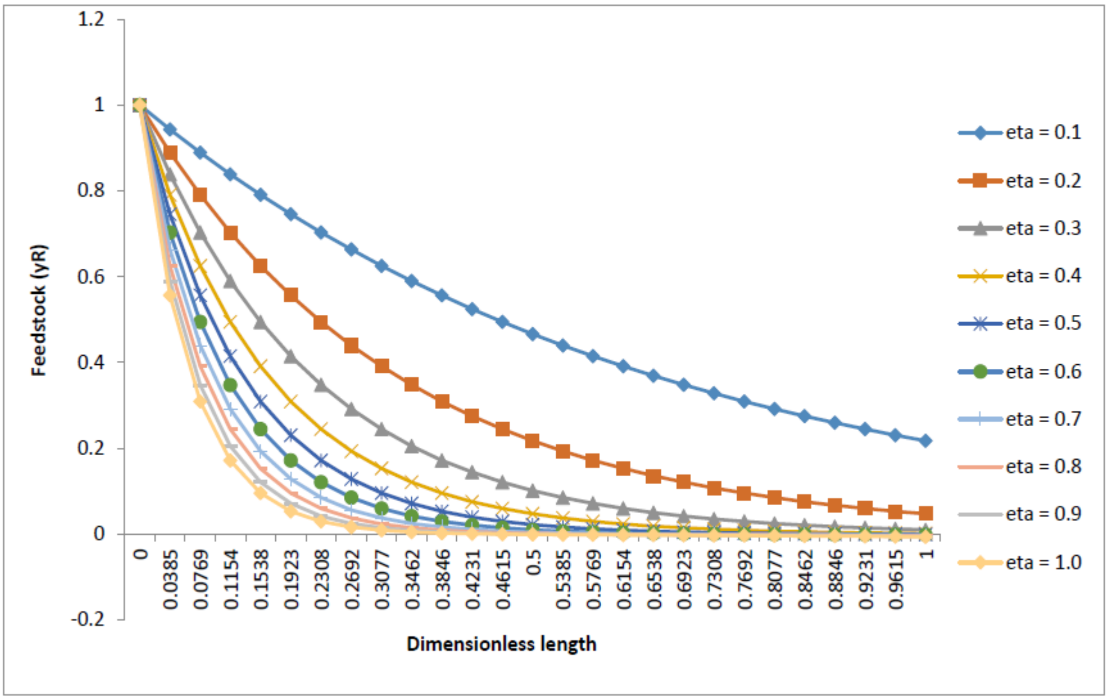

Fig. 12. Feedstock depletion along reactor dimensionless length.

2) Variation of light gases with reactor dimensionless length

The hydrocracker reactor's first product is light ends gases (liquefied petroleum gas), and the yield of this product rises throughout the reactor's dimensionless length to a maximum value or yield before becoming steady or constant. As a result, as shown in Fig. 13, the light ends product yield rises as the catalyst effectiveness factor varies.

As the hydrocracking process continues, the production of light ends gas rises and reaches its maximum yield at reactor dimensionless length of 0.2692 before beginning to yield steadily throughout reactor dimensionless length.

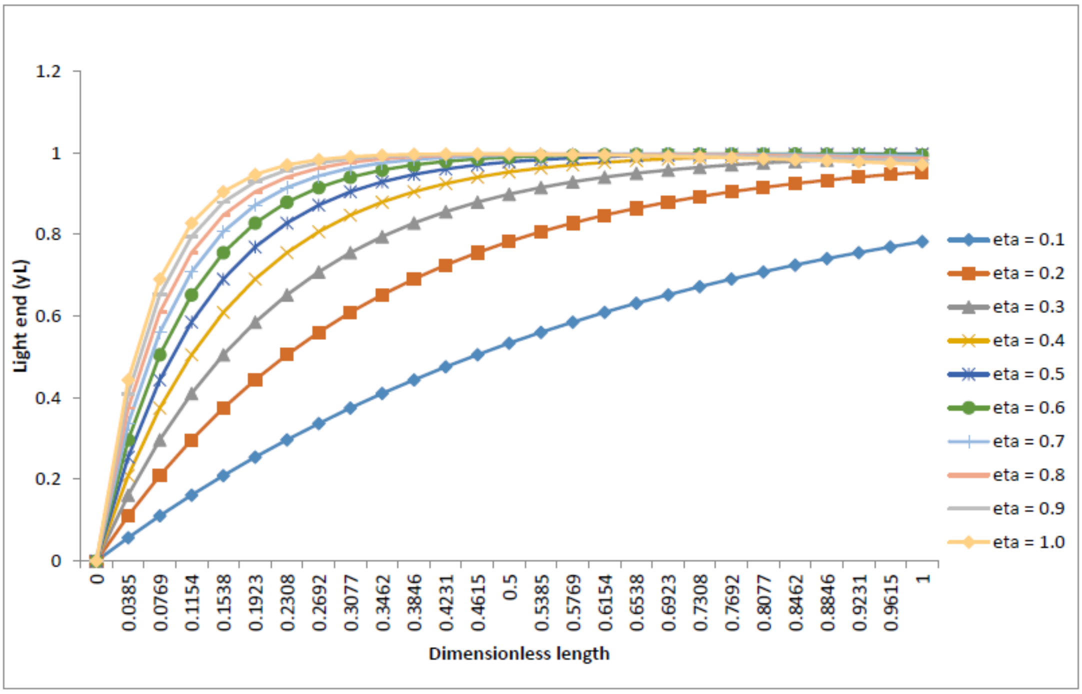

Fig. 13. Light ends product yield along reactor dimensionless length.

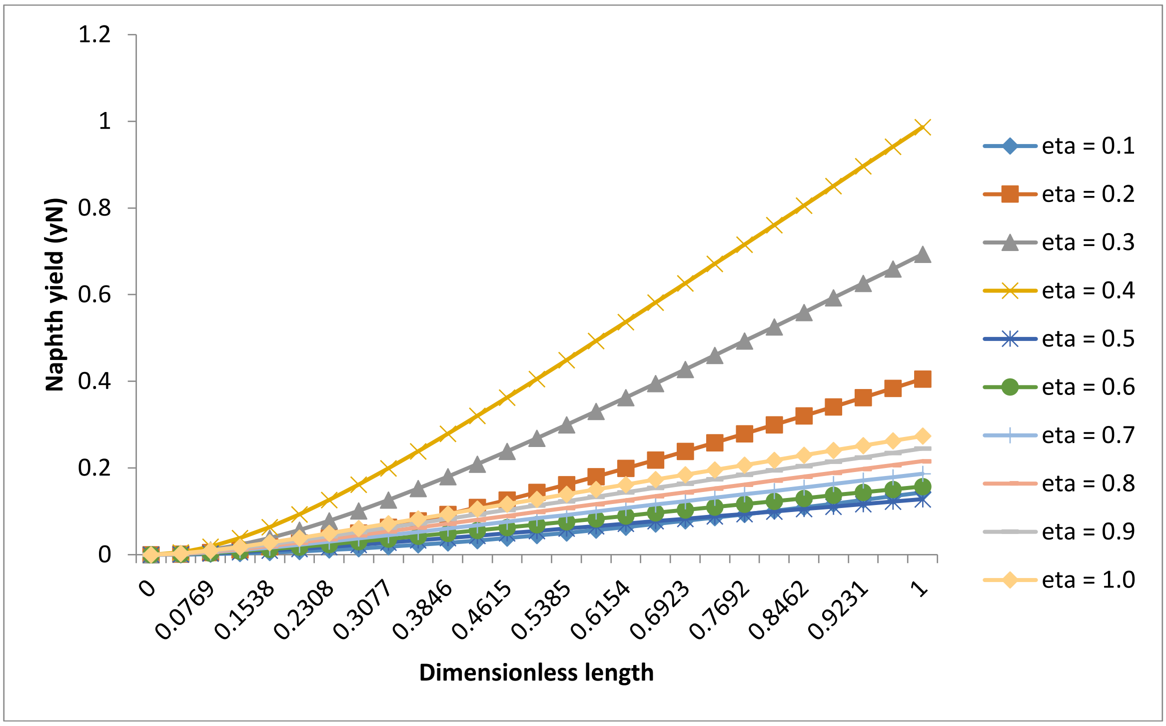

Fig. 14. Naphtha product yield along reactor dimensionless length.

3) Variation of naphtha product yield with reactor dimensionless length

Since light ends products emerge first as the hydrocracking process advances, naphtha production in the hydrocracker reactor begins at a reactor dimensionless length of 0.0769. According to Fig. 14, the formation of light ends product prevented the formation of naphtha product as the hydrocracking process started up to a reactor dimensionless length of 0.0769. However, there has been a steady increase in the yield of naphtha product along the reactor's dimensionless length from 0.0769 to 1 at various catalyst effectiveness factors. As a result, over the dimensionless length of the reactor, the yield of the naphtha product increases steadily. The highest yield occurs at high catalyst effectiveness factors, while the minimal yield is recovered at catalyst effectiveness factors of 10%.

4) Variation of diesel product yield with reactor dimensionless length

As shown in Fig. 15, the yield of diesel product along the reactor's dimensionless length was also determined at various values of the catalyst effectiveness factor. Up to dimensionless length 0.1923, there was no diesel product yield at the hydrocracker reactor's inlet, but from that point on, the yield steadily increased to 1. Because light ends and naphtha products were produced before diesel products, the yield of the diesel product was first observed at reactor dimensionless length of 0.1923. From there, the yield of the diesel product gradually increased along the reactor dimensionless length, reaching its maximum at 80% catalyst effectiveness.

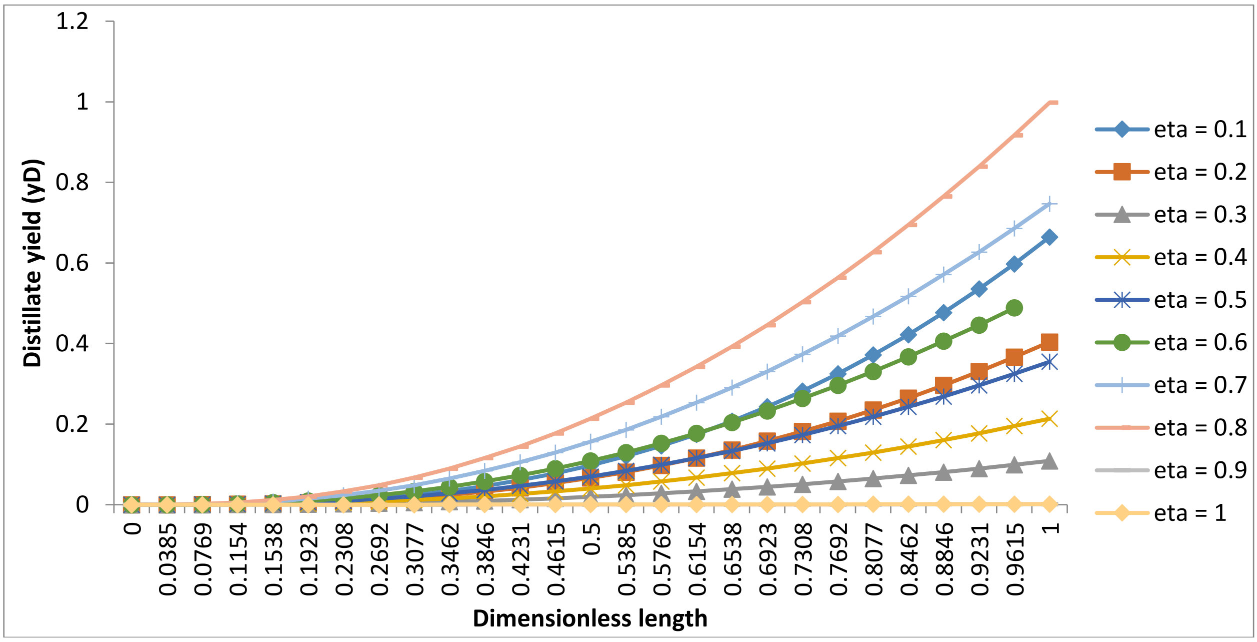

Fig. 15. Distillate product yield along reactor dimensionless length.

5) Variation of bottom product yield with reactor dimensionless length

Unconverted feedstock is referred to as the hydrocracker reactor's bottom product, which is a mixture of liquid and vapour fractions that can be recycled with the new feedstock (residue) into the hydrocracker reactor for continuous operational process or further sent for another process operation as may be desired. As shown in Fig. 16, due to the formation or yield of light ends, naphtha, and diesel products, the bottom product yield along the reactor's dimensionless length was not realized until 0.2693. Except for catalyst effectiveness factor 0.3, which showed a bottom product yield at reactor dimensionless length of 0.3077, this pattern persisted for catalyst effectiveness factor values up to 0.4615 reactor dimensionless length.

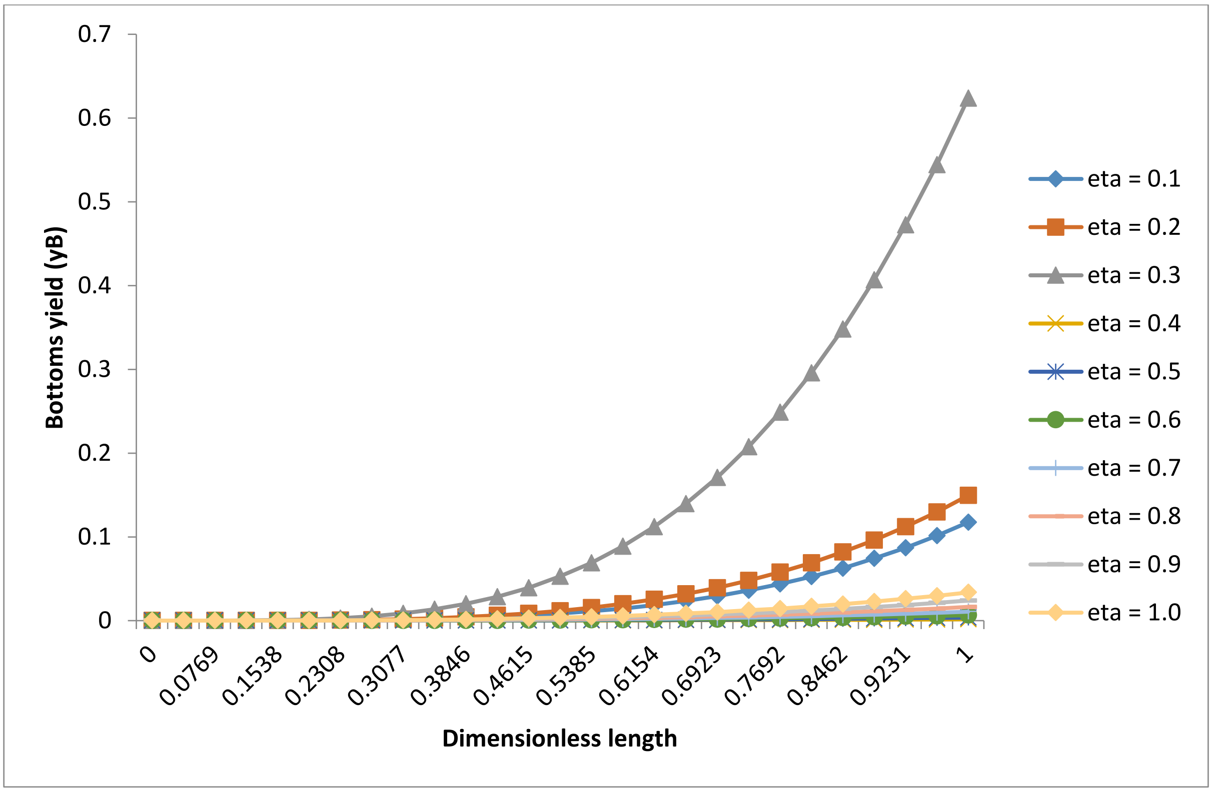

Fig. 16. Bottom Product yield along reactor dimensionless length.

A high catalyst efficiency factor (active catalyst) is therefore necessary in general for greater desired product yield with a low bottom product yield.

V. Conclusion

The research focal point is on improved or enhanced production from 30,000 bpd capacity conventional modular refinery (topping plant) operations in Nigeria via its modification. In achieving the aim of the study, some objectives were highlighted and achieved that included analysis and classification of twenty different types of Nigerian crude oil as light and medium sweet crude based on API value and sulphur content, and categorised into three groups based on recovery volume at operating temperature of 370°C. The classified crude oil types (Akpo 2011 and Okoro 2012) were simulated in conventional and modified modular refinery (topping plant) of twenty-nine column trays based on the recovery volume and equipment cost analysis at this column tray. Additional valuable products (liquefied petroleum gas, naphtha and diesel) were produced from conventional modular refinery residue as feedstock into the hydrocracker reactor attached to the stripping section of the modified modular refinery process. The nature of the hydrocracker reactor was determined to be isothermal based on operational process taking place in the reactor, performance models were developed from first principle in predicting feedstock (residue) depletion and products (light ends, naphtha, diesel and bottom) yield of the hydrocracker using a five lump scheme. Furthermore, the reaction kinetic parameters such as pre-exponential factors and activation energies were estimated using single point regression analysis with MatLab software, thereby solving the developed models. The developed performance models results were compared with Aspen Hysys yields of the hydrocracker, evaluated kinetic parameters (pre-exponential factors and activation energies) compared with experimental results of kinetic parameters of similar hydrocracker study with deviation or absolute error less than 1% and the hydrocracker reactor was simulated at different degree of catalyst effectiveness factors. Therefore, modified modular refinery operations can resolve the difficulties or constraints associated with conventional modular refinery operation in Nigeria due to inefficient major refineries and inaccessible road network for tanker delivery coupled with poor pipeline networks for delivery of residue to main refinery for further operational process. However, the major weakness of this study is the bottom product of the hydrocracker, which can be processed via other secondary refining process.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Prof J. G. Akpa is the chairman of the supervisory committee that initiated this research study as a panacea to environmental degradation and devastation caused by local refinery operators in Nigeria. other members of the supervisory committee include Prof. K. K. Dagde and Dr. E. O. Ehirim also, Dr. O. M. Adeloye conducted the research, data analysis and compilation of research results as accepted by all members of the supervisory committee. Thus, all authors had approved the final version of this research for publication.

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