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# Optimization of the Striping Section of Modular Refinery Operations in Nigeria

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## Abstract

Nigerian crude oil type Okoro 2012 was applied in this study owing to its low API value 23.54 and high residual percentage value of 42.16% from conventional modular refinery operations in Nigeria. The residue acted as a precursor or feedstock to the hydrocracker reactor of the modified modular refinery operation, which is an hydrogenation catalytic process at operating conditions of 380˚C and 183 bar respectively and the hydrogen gas applied is produced via steam-methane reforming since the operational feedstocks are available as methane is the first gaseous product from the modified modular refinery process. Thus, more valuable products such as liquefied petroleum gas, naphtha and diesel were produced from modified modular refinery thereby resolving the residue or bottom product issue associated with conventional modular refinery operation in Nigeria. Models were developed from the first principle through the application of the principle of conservation of mass to predict the performance of the hydrocracker reactor and the developed models were sets of ordinary differential equations, which were solved using MatLab ODE45 solver and validated using simulation data of Aspen Hysys software for the hydrocracker reactor. The results gave a minimum percentage absolute error (deviation) between model predictions and Aspen Hysys results of 4.45%, 5.0% and 2.02% for liquefied petroleum gas, naphtha and diesel products respectively. Hence, the model developed predicted the output performance of the hydrocracker reactor very closely and was applied in studying or simulation of the effects of catalyst effectiveness factor on the overall performance of the hydrocracker reactor.

## Keywords

Simulation, Optimization, Okoro 2012, Hydrocracker, Five Lump, Aspen Hysys, MatLab

## 1. Introduction

A modular refinery can be built and operational within fourteen months of contract execution, thereby providing valuable fuels for host communities for vehicles, power generation, water treatment, and employment chances [1]. The components of modular refinery include tankage, a distillation unit, facilities for gas recovery, and light hydrocarbons, and utility systems such as steam, power, and water-treatment plants. Topping refineries yield large amounts of unprocessed product (residue) and local markets determines its installation. The modular refinery process gives high quality control level, effective application of space and pre-delivery testing for efficient process functionality. Its available capacities range between 1000 and 30,000 barrels per day (bpd) [2]. Topping refineries are hastily becoming a viable, flexible and cost effective scheme for petroleum producers especially where there is quick requirement to meet local need of crude oil products with relatively low investment cost; quick and construction period are some of the major advantages of a modular refinery [3]. The manufacture of modular refineries is carried out in a production platform in tandem with the operator's full specification [4]. Thus, a modular refinery is defined as a process plant built wholly on skid mounted structures with each structure consisting of a part of the whole process unit, and components linked together via pipeline networks and an easily manageable operation [2]. The simplest and economical refinery configuration of modular refinery is called a topping refinery, and this is designed to produce diesel, kerosene, naphtha and liquefied petroleum gas with its residue as its by-product [5].

Petroleum is mainly a mixture of different hydrocarbons of varying compositions and complexities. Crude oil separation into its different fractions that make up the raw natural resource involves crude oil refining (refinery process) and components are removed according to their temperature difference (boiling points) [4]. Thus, the Nigeria government owns and operates four major refineries through the Nigerian National Petroleum Corporation (NNPC) namely, old and new Port-Harcourt Refining Company (OPHRC and NPHRC), Kaduna Refining and Petrochemical Company Limited (KRPC) and Warri Refining and Petrochemical Company Limited (WRPC). Despite these refineries, 80% of petroleum products consumed in Nigeria are based on importation as the refineries operate less than 20% to 25% of its original capacities [6] [7] [8]. Therefore, the dependency on importation of petroleum products in Africa's largest crude oil producer, Nigeria has led to incessant and continual scarcity of petroleum products. In addition, illegal refineries that feed on stolen crude oil are common in Nigeria with its associated operational and production hazards such as environmental pollution, crude oil theft, fire safety risk and poor quality petroleum products etc. [9]. To curb the incessant and continual scarcity of petroleum products, environmental hazard associated with illegal (local) refineries, and reducing to minimal the importation of petroleum products, the existing refineries need to be revamped and operated at full capacity; while new refineries are built by partnering with private sector, this will enhance deregulation of the sector [10]. Since construction of major refineries are capital intensive and time consuming, modular refineries have been licensed as a panacea to scarcity of petroleum products to meet local demands in Nigeria, thereby enhancing the availability of good quality products by eliminating illegal refineries and its associated environmental hazards.

However, conventional modular refineries (topping plants) have been reported with associated issue of bottom product (residue) as many researches are silent with this bottom product [1] [5] [6] [11] [12] and the stripping section residue or bottom product depends on the type and nature of crude, which are determine by several parameters such as API, sulphur content, Watson characterization factor etc. Hence, network of pipelines or tankers are generally used in developed countries for transporting modular refinery (topping plant) residue to conventional major refinery for further operational processes. However, this is not obtainable in Nigeria due to the topography of the country and low operational efficiency (below 15%) of the conventional major refineries.

Hence, the significance of this research is based on the need to improve and enhanced the quality of products and ensure availability of petroleum products in Nigeria by proposing a twenty-nine (29) trays modified modular refinery (topping plant) that can further process the residue from conventional modular refinery to more valuable products via hydrocrackerreactor attached to the stripping section of the crude distillation unit of the modular refinery using Aspen Hysys software, and development of models for hydrocracker by using a five lumpreaction scheme. Therefore, this research study is focused on optimization of petroleum refined products from conventional modular refinery operations in Nigeria through the processing of its residue to more valuable products such as liquefied petroleum gas, naphtha and diesel via a hydrocracker reactor.

## 2. Materials and Method

Some of the materials applied in this research study include Okoro 2012, modified conventional modular refinery, residue, five lump scheme, Aspen Hysys, MatLab software, Hence, the research procedures are as follows.

### 2.1. Process Operation of Modified Modular Refinery

The crude oil sample applied in this study has the least API (23.54) value among many Nigerian crude oil types as classified by Adeloye (2022) and tends towards heavy crude oil type (API value below 22) as highlighted [4]. Also, twenty-nine (29) column trays of the crude distillation unit were applied in the modified modular refinery with hydrocracking reactor attached to its stripping section as shown in **Figure 1**. Hence, Okoro 2012 was simulated in a modified modular refinery at operating temperature of 370˚C to yield products such as off gas, naphtha, kerosene, diesel, atmospheric gas oil and residue. The residue, which is the stripping section product or bottom product of the conventional modular

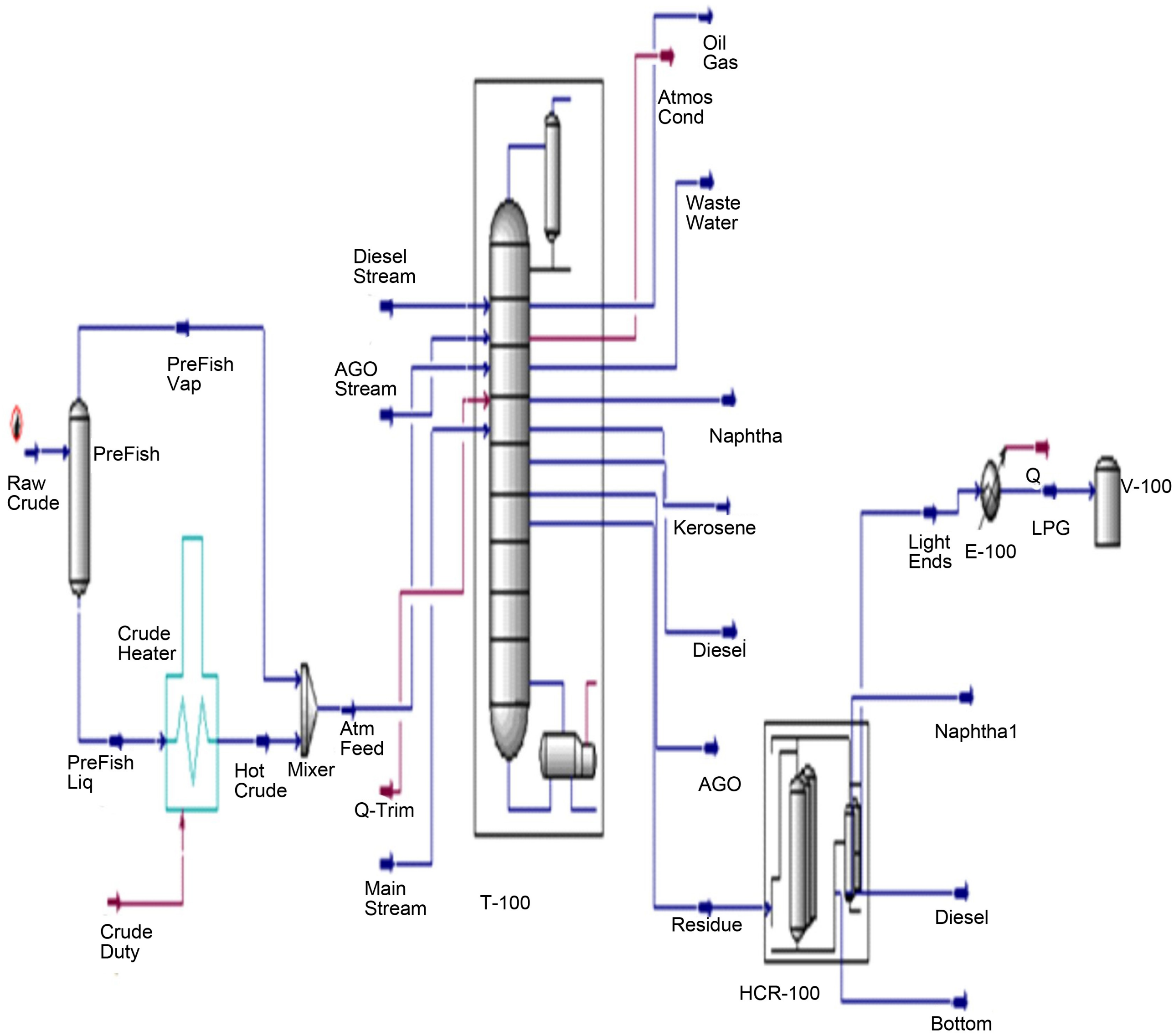


Figure 1. Modified conventional modular refinery.

refinery is sent as feedstock for further process or simulation via the hydrocracking reactor attached to the stripping section of the conventional modular refinery. The off gas product which is mainly methane is reformed via methane steam reforming process to produce hydrogen gas for the hydrocracker operation. The residue is therefore hydrocracked in the presence of Nickel supported catalyst and hydrogen gas to produce liquefied petroleum gas, naphtha, diesel and bottom product. The hydrogen gas is so useful such that any trace of olefins and di-olefins produced during cracking operation are converted to their respective paraffin (saturated products) and the simulation processes was carried out on the basis of 30,000 barrel per day (902.1 Kgmol/hr) of Okoro 2012.

## 2.2. Development of Model Equations for Hydrocracking Reactor

The hydrocracker unit of the modified conventional modular refinery is modeled to predict the reactor performance and product yield.

#### 2.2.1. Five Lumps Kinetic Scheme

The five lumps system applied in this study include the feedstock (conventional modular refinery bottom product or residue) and products from hydrocracker that include light ends, naphtha, diesel and bottom. The reaction pathway for the hydrocracking process for five lumps system is shown in Figure 2.

#### 2.2.2. Rate Equations and Kinetics of Five Lumps Process

The rate equations of the five lump system applied in this study with their respective kinetic parameter expression using Arrhenius equation are described in this section.

**1) Rate Equation of Feedstock**

Based on the reaction lumping path in Figure 2, the rate of reaction for the feedstock (residue) in terms of mass fraction is expressed as

$$-r_R = -\left(k_L y_L + k_N y_N + k_D y_D + k_B y_B\right)\eta \tag{1}$$

**2) Rate Equation of Light End Product**

The rate equation for the production of light end in terms of mass fraction is described thus

$$-r_L = -k_L y_L \eta \tag{2}$$

**3) Rate Equation of Naphtha Product**

The hydrocracking product (naphtha) rate equation in terms of mass fraction is expressed as

$$-r_N = -k_N y_N \eta \tag{3}$$

**4) Rate Equation of Diesel Product**

The reaction rate equation describing the production of diesel via hydrocracking process is expressed in terms of mass fraction

$$-r_D = -k_D y_D \eta \tag{4}$$

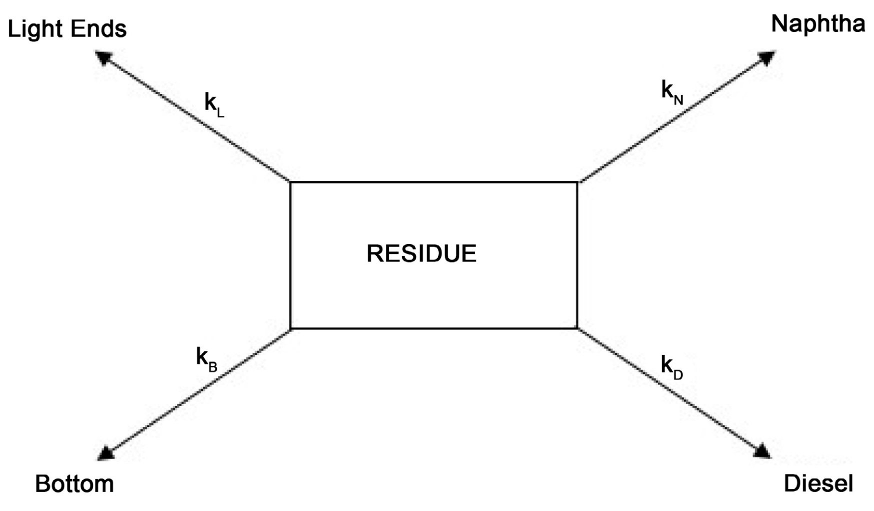


Figure 2. Five lumps model scheme for hydrocracking reactor.

**5) Rate Equation of Bottom Product**

The rate equation for the production of bottom product in the hydrocracking of feedstock in terms of mass fraction

$$-r_B = -k_B y_B \eta \tag{5}$$

In addition, the reaction rate constants in Equations (1) to (5) for the conversion of feedstock and production of light end, naphtha, diesel and bottom products are evaluated from Arrhenius equation.

$$k_i = k_0 \exp\left(\frac{-E_i}{RT}\right) \tag{6}$$

Therefore, writing the reaction rate constants for respective reaction path of the five lump scheme.

**1) Light End**

$$k_L = k_{L0} \exp\left(\frac{-E_L}{RT}\right) \tag{7}$$

**2) Naphtha**

$$k_N = k_{N0} \exp\left(\frac{-E_N}{RT}\right) \tag{8}$$

**3) Diesel**

$$k_D = k_{D0} \exp\left(\frac{-E_D}{RT}\right) \tag{9}$$

**4) Bottom**

$$k_B = k_{B0} \exp\left(\frac{-E_B}{RT}\right) \tag{10}$$

### 2.2.3. Model Equations for Hydrocracking Reactor

In developing model equations that predicts the optimal performance of hydrocracker, the following assumptions are applied.

1) The rate of hydrocracking does not depend on hydrogen concentrations and there is excess availability of hydrogen gas [13] [14] [15].

2) The reaction rate does not depend on hydrogen gas partial pressure.

3) The feedstock and all products are in the liquid phase and hydrogen feed is pure [14].

4) The reaction paths of the hydrocracker process is first order reaction and steady state operations.

Through the application of the law of conservation of mass, the general material balance equation for a packed bad catalytic hydrocracker reactor shown in **Figure 3** by considering the differential length (dl ) is expressed as

$$\begin{aligned}&\text{Rate of Accumulation of Material into the Reactor}\\&= \text{Rate of inflow into the reactor} - \text{Rate of outflow from the rector}\\&\pm \text{Rate of production or depletion within the reactor due to chemical reaction}\end{aligned} \tag{11}$$

Substituting and mathematical analysis of Equation (11) yields

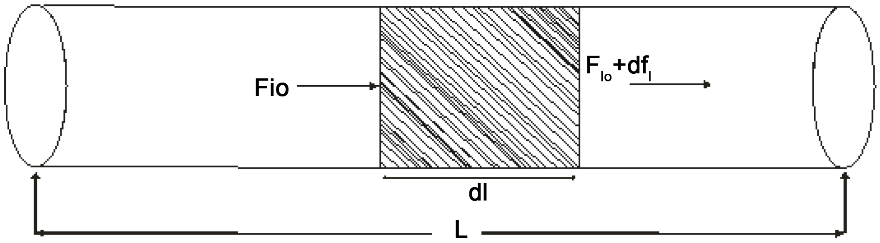


Figure 3. Packed bed catalytic hydrocracker.

$$\frac{\mathrm{d}y_i}{\mathrm{d}l_d} = -\tau\varepsilon(-r_i) \tag{12}$$

Therefore, the general change in mass fraction of specie (feedstock and products) in terms of dimensionless length is expressed by Equation (12).

### 2.2.4. Hydrocracking Reactor Performance Evaluation

In describing the performance evaluation of the hydrocracking reactor, the feedstock depletion and products yields are analyzed by applying the developed model equations and the resulting equations are sets of ordinary differential equations.

**1) Feedstock (Residue)**

The model equation describing the depletion of feedstock mass fraction along the hydrocracking reactor dimensionless height yields

$$\begin{aligned}\frac{\mathrm{d}y_R}{\mathrm{d}l_d} = -\tau\eta\varepsilon\bigg(& k_{L0}\exp\left(\frac{-E_L}{RT}\right)y_L + k_{N0}\exp\left(\frac{-E_N}{RT}\right)y_N \\ &+ k_{D0}\exp\left(\frac{-E_D}{RT}\right)y_D + k_{B0}\exp\left(\frac{-E_B}{RT}\right)y_B\bigg)\end{aligned} \tag{13}$$

**2) Light Ends**

The model equation predicting the yield of light ends (Liquefied petroleum gas) product from the hydrocracking reactor

$$\frac{\mathrm{d}y_L}{\mathrm{d}l_d} = \tau\varepsilon\eta k_{LO}\exp\left(\frac{-E_L}{RT}\right)y_L \tag{14}$$

**3) Naphtha**

The yield of the naphtha product from the reactor is expressed thus.

$$\frac{\mathrm{d}y_N}{\mathrm{d}l_d} = \tau\varepsilon\eta k_{NO}\exp\left(\frac{-E_N}{RT}\right)y_N \tag{15}$$

**4) Diesel**

The diesel product yield along the reactor dimensionless length or height is evaluated as

$$\frac{\mathrm{d}y_D}{\mathrm{d}l_d} = \tau\varepsilon\eta k_{DO}\exp\left(\frac{-E_D}{RT}\right)y_D \tag{16}$$

**5) Bottom**

The bottom product yield from the hydrocracking reactor is deduced as

$$\frac{\mathrm{d}y_B}{\mathrm{d}l_d} = \tau\varepsilon\eta k_{BO} \exp\left(\frac{-E_B}{RT}\right) y_B \tag{17}$$

#### 2.2.5. Solution Technique

The developed model equations for the hydrocracker are sets of linear differential equation that are numerically solved using the Runge-Kutta algorithm for fourth order coupled in MatLab solver to determine the feedstock conversion and products (light ends, naphtha, diesel and bottom) yield along the reactor dimensionless length. These results were validated with the Aspen Hysys result of the modified conventional modular refinery to test the suitability of the models in predicting the conversion or yield of the feedstock or products from the reactor. The specification of nickel based catalyst applied in the hydrocracker operation is shown in Table 1, while the hydrocracking reactor's process operating conditions were depicted in Table 2. Also, the five lump reaction scheme operating parameters such as pre-exponential factors and activation energies applied in this study is based on the kinetic parameters estimated values by Adeloye (2022) [4] and highlighted in Table 3.

**Table 1.** Catalyst specifications for hydrocracker [14] [16].

| Properties | Value |
|---|---|
| Shape | Spherical |
| Mesh | 10 - 20 |
| Bulk Density | 654 kg/m$^3$ |
| Density (Solid) | 2500 kg/m$^3$ |
| Surface Area | 270 m$^2$/g |
| Effectiveness Factor | 0.8 |
| Void Fraction | 0.26 |

**Table 2.** Reactor operating parameters [13] [14].

| 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 (380˚C) | ˚C |
| Porosity of Catalyst Bed | 0.345 - 0.55 | - |
| Bulk Density of Bed | 654 | kg/m$^3$ |
| Diameter of Particle | $2 \times 10^{-3}$ | m |

**Table 3.** Five lumps kinetic parameters [4].

| Parameters | Light Ends | Naphtha | Diesel | Bottom |
|---|---|---|---|---|
| Activation Energy (kcal/mol) | 5.6151 | 41.3388 | 48.5074 | 23.5293 |
| Frequency Factor (m$^2$ hr$^{-1}$ m$^3$ Cat$^{-1}$) | 51.9547 | 9.2999E8 | 2.3399E16 | 2.25E8 |

## 3. Results and Discussion

The results obtained from the Aspen Hysys simulation of Okoro 2012 (Nigerian crude oil type) in conventional and modified modular refinery processes in terms of products yield are depicted in Figure 4 and Figure 5 respectively.

The conventional modular refinery yielded products with recovery percentages as light straight chain (7%), naphtha (14.88%), kerosene (10%), diesel (20.96%), atmospheric gas oil (5%) and residue (42.16%) respectively. Thus, the residue product percent of the conventional topping plant is extremely high and further operational process is required to enhance more petroleum products yield. In addition to the above products yield, the conventional modular refinery residue was applied as feedstock to hydrocracker reactor of the modified modular

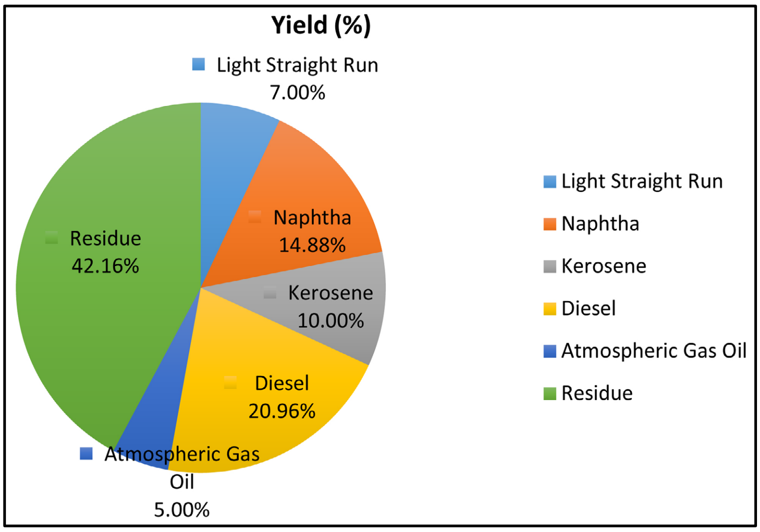


Figure 4. Okoro 2012 products yield from conventional modular refinery.

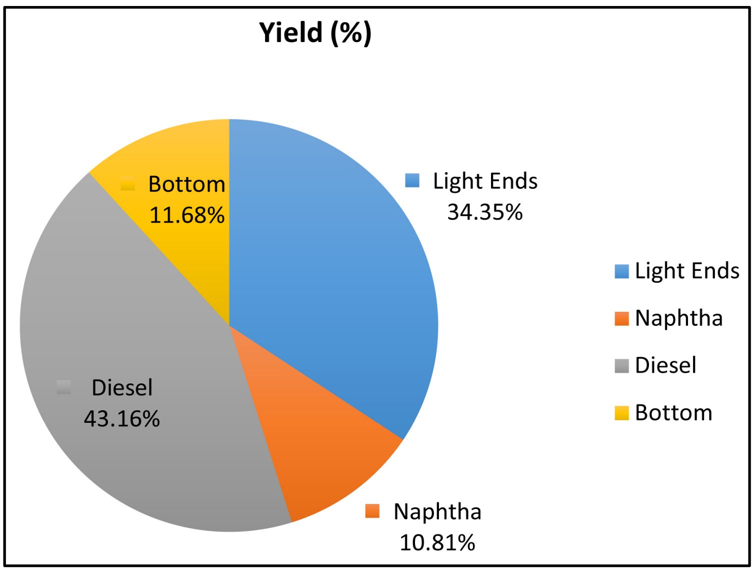


Figure 5. Products yield of hydrocracker reactor in modified modular refinery residue.

refinery in order to optimize, enhanced or improved petroleum products yield and also environmental friendly operation of the conventional modular refinery.

It can be deduced from above figure that more valuable products such as light ends (liquefied petroleum gas), naphtha and diesel were produced from the conventional modular refinery residue or bottom product via the modified modular refinery operational process. These products are of great importance and needs in Nigeria for both domestic and industrial applications, thus, the residual product yield of conventional and modified modular refinery processes for Okoro 2012 (Nigerian crude oil type) were compared as shown in **Table 4**.

Thus, the modified modular refinery (conventional modular refinery with hydrocracker reactor attached to the stripping section), yielded a relatively low residual yield of 4.92% in comparison with the conventional modular refinery residual yield of 42.16%. Hence, the modified modular refinery has reduced to minimum the residual percentage constraint or issue associated with conventional modular refinery operations in Nigeria due to inefficient conventional major refineries.

## 4. Model Validation and Simulation

The results of the Aspen Hysys and developed models for hydrocracker reactor using Okoro 2012 residue as feedstock were compared and validated.

### 4.1. Model Validation

The validation of the operational process of this research study is shown in **Table 5**.

The comparison of products yield of hydrocracker with Okoro 2012 residue as feedstock from both Aspen Hysys and developed models showed minimal error or absolute deviation value as shown in **Table 5**, thereby verifying the effectiveness or accuracy of the applied kinetic parameters (pre-exponential factors and

**Table 4.** Residual product percent of conventional and modified modular refinery.

| Crude Oil Type | Residue (%) | |
|---|---|---|
| | Modular Refinery | Modified Modular Refinery |
| Okoro 2012 | 42.16 | 4.92 |

**Table 5.** Aspen Hysys and developed models yield of hydrocracker.

| Parameters | Aspen Hysys Yield | 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 |

activation energies) by Adeloye (2022) [4] and consequently, the predicted models, thus models' application for simulation of hydrocracker reactor.

## 4.2. Model Simulation

Based on the validation of the developed models, models simulation was performed to study the effects of catalyst effectiveness factors on feedstock conversion and products yield of the hydrocracker reactor.

### 4.2.1. Variation of Feedstock with Reactor Dimensionless Length

The conversion or depletion of feedstock (Okoro 2012 residue) in the hydrocracking reactor along the reactor dimensionless length was studied at various degree of the catalyst effectiveness factors as shown in Figure 6.

Thus, Figure 6 showed a depletion trend thereby affirming to feedstock (reactant) consumption for all values of catalyst effectiveness factor. Thus, the depletion of feedstock is faster at effectiveness factor of 80% and 90% respectively with feedstock approaching zero at reactor dimensionless length of 0.3846. Also, the feedstock conversion rate was least at 10% catalyst effectiveness factor

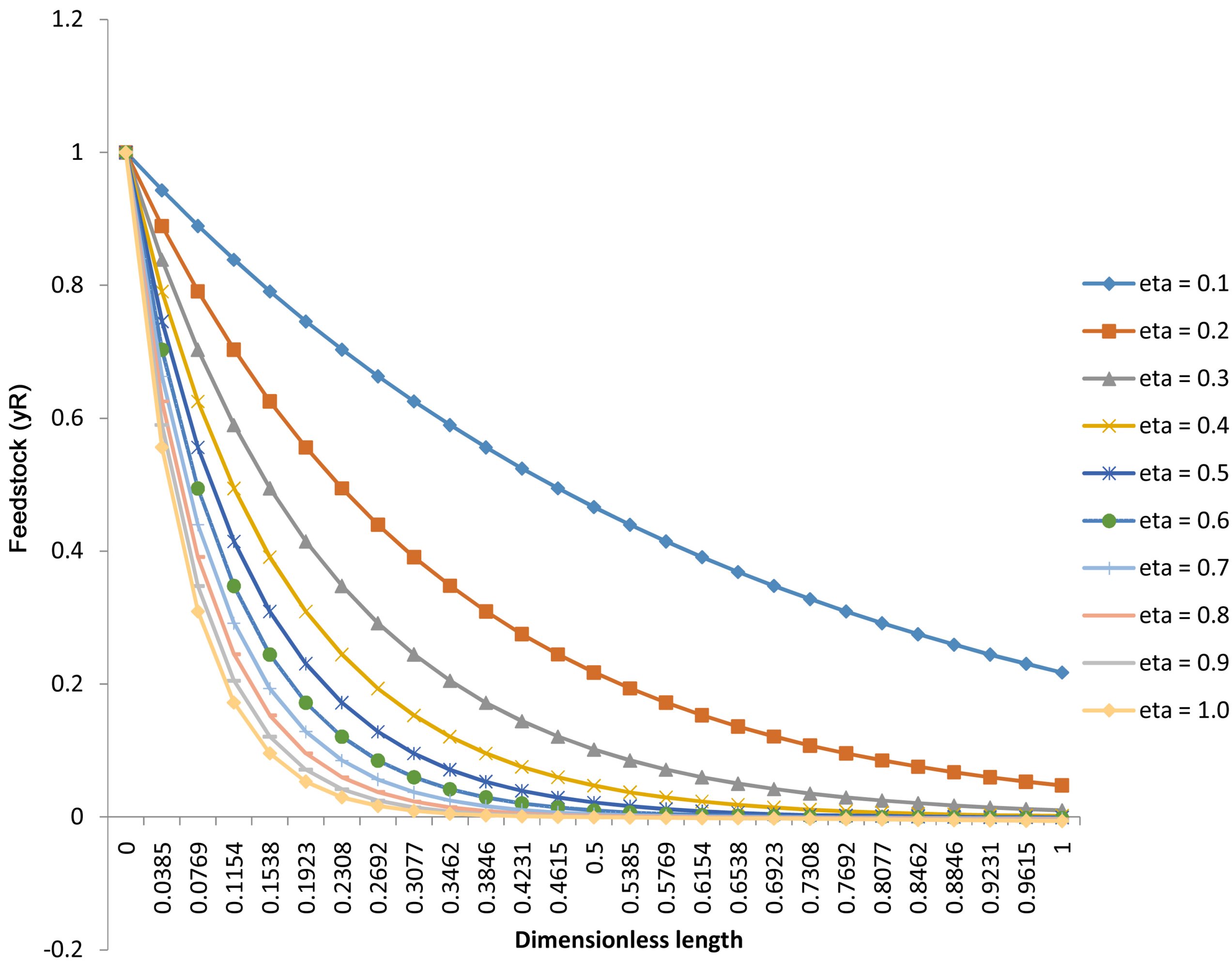


Figure 6. Feedstock depletion along reactor dimensionless length.

and feedstock conversion increases as catalyst effectiveness factor increases. Therefore, at high catalyst effectiveness factor, the conversion of feedstock in the hydrocracking reactor is faster due to catalyst activity.

#### 4.2.2. Variation of Light Ends with Reactor Dimensionless Length

The light ends (gases) are the first product from the hydrocracking reactor. The yield of the light ends product increases along the reactor dimensionless length to a maximum yield before its steady or constant yield. Thus, the light ends product yield increases as the catalyst effectiveness factor changes as depicted in Figure 7.

The production of light ends (gases) increases as the hydrocracking process proceeds and approaches maximum yield at reactor dimensionless length of 0.2692 before its steady yield along the reactor's dimensionless length. Hence, the yield of the light ends product is minimum along the reactor dimensionless length at effectiveness factor of 10% in comparison to other catalyst effectiveness factors.

#### 4.2.3. Variation of Naphtha Product Yield with Reactor Dimensionless Length

The production of naphtha in the hydrocracking reactor starts at reactor dimensionless length of 0.0769, and this is due to the light ends product formation first as the hydrocracking process proceeds.

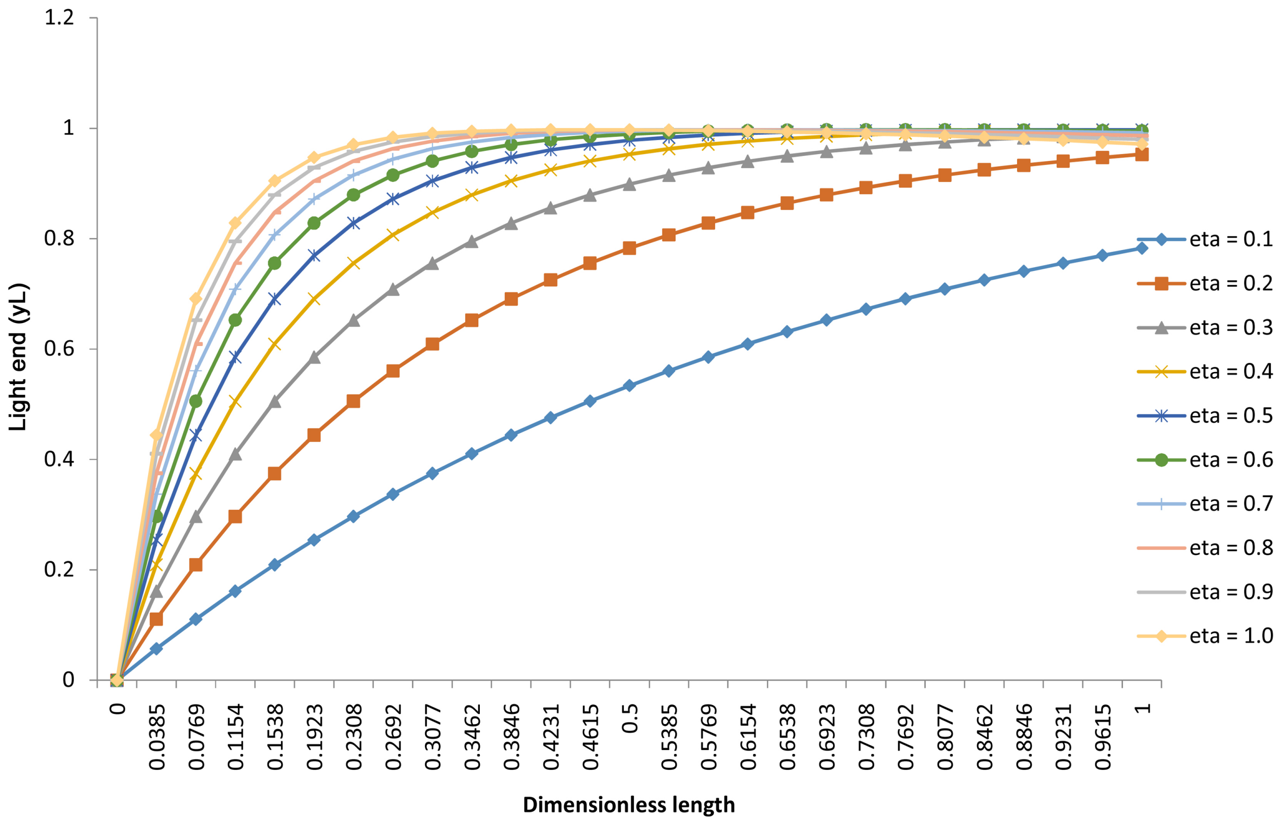


**Figure 7.** Light ends product yield along reactor dimensionless length.

As shown in Figure 8, there was no naphtha product formation as the hydrocracking process commences to a reactor dimensionless length of 0.0769 owing to the formation of light ends product. Thus, there is continuous change in the yield of naphtha product along the reactor's dimensionless length from 0.0769 to 1 at different catalyst effectiveness factors. Therefore, the yield of the naphtha product increases steadily along the reactor dimensionless length with maximum yield occurring at high catalyst effectiveness factor, while the minimum yield is recovered at 10% catalyst effectiveness factor.

#### 4.2.4. Variation of Diesel Product Yield with Reactor Dimensionless Length

The yield of diesel product along the reactor dimensionless length was also evaluated at different value of catalyst effectiveness factor as highlighted by Figure 9. There was no distillate product yield between the reactor inlet and dimensionless length 0.1923, but a steady increase in distillate yield from reactor's dimensionless length 0.1923 to 1.

As depicted in Figure 9, the distillate yield was first seen at reactor dimensionless length of 0.1923 owing to the production of light ends and naphtha products before the distillate product. Furthermore, there is a gradual increase of the distillate yield along the reactor dimensionless length and maximum distillate yield is achieved at 80% catalyst effectiveness factor.

#### 4.2.5. Variation of Bottom Product Yield with Reactor Dimensionless Length

The bottom product refers to unconverted feedstock in the hydrocracking reactor. As shown in Figure 10, there was no bottom product yield along the reactor

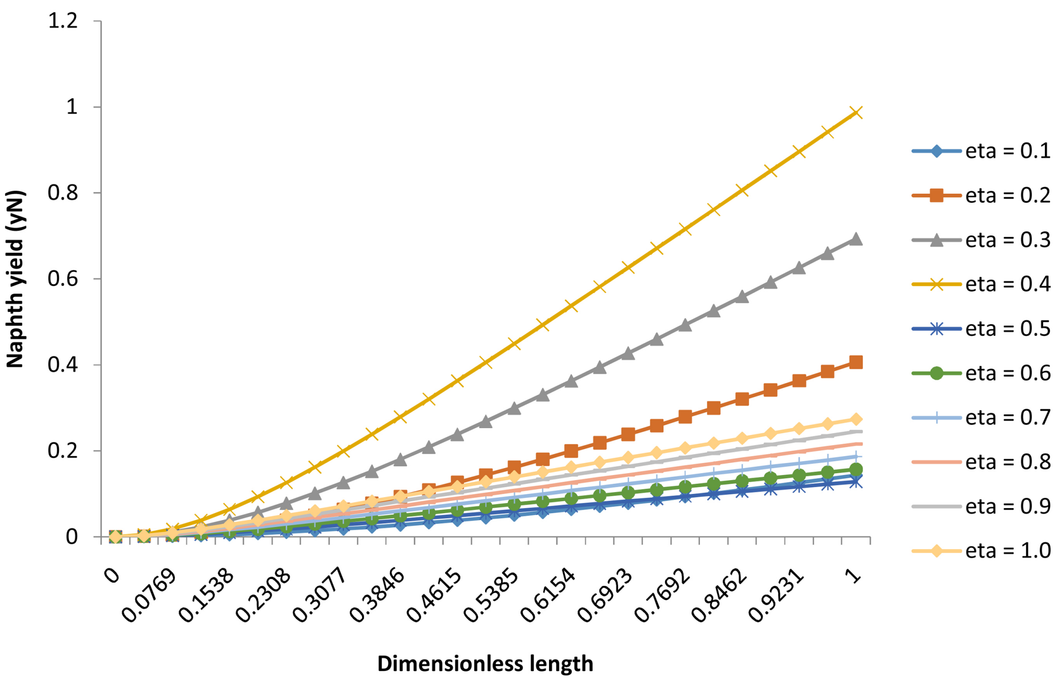


Figure 8. Naphtha product yield along reactor dimensionless length.

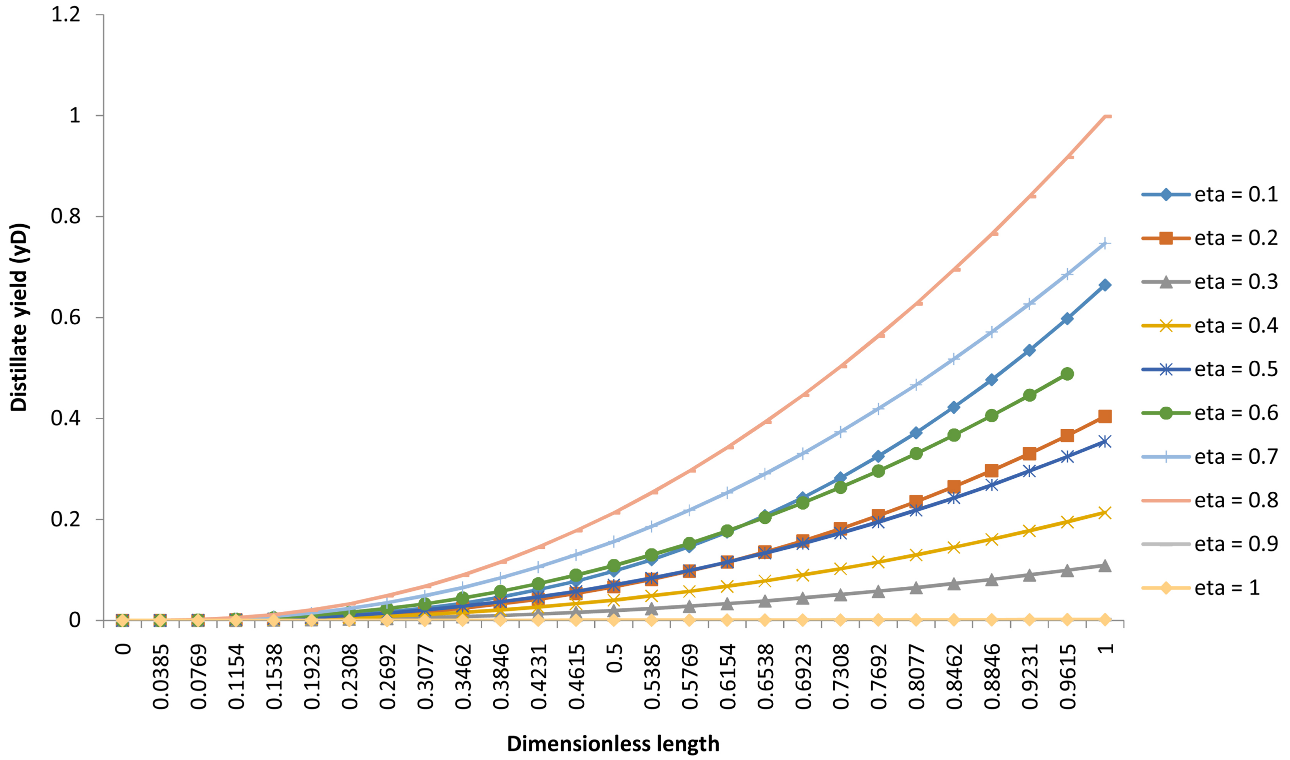


**Figure 9.** Distillate product yield along reactor dimensionless length.

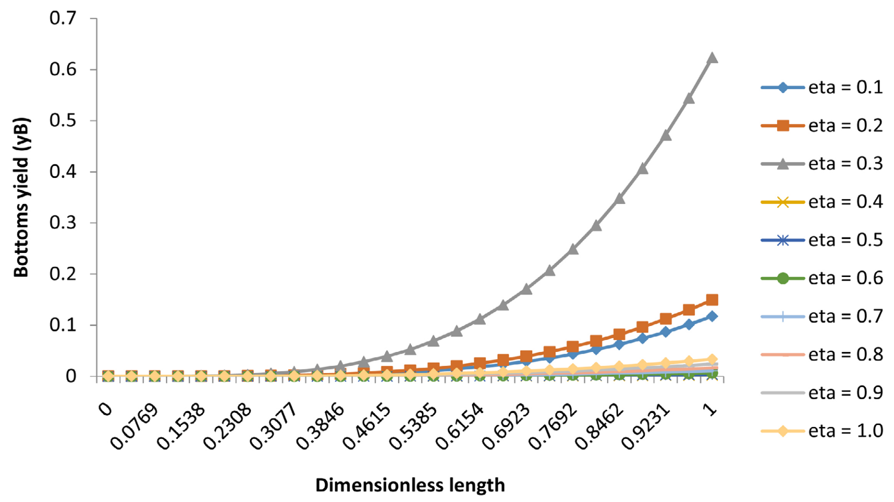


**Figure 10.** Bottom product yield along reactor dimensionless length.

dimensionless length until 0.2693 owing to the formation or yield of light ends, naphtha and distillate products. This trend was steady for catalyst effectiveness factor values up to 0.4615 reactor dimensionless length except for catalyst effectiveness factor 0.3 (30%) in which bottom product yield was observed at reactor dimensionless length of 0.3077.

Therefore, high catalyst effectiveness factor is required (active catalyst) for more desired product formation with minimal bottom product yield (as the bottom product yielded the least percentage among the products).

## 5. Conclusion

Optimization of conventional modular refinery operations in Nigeria was achieved via the addition of hydrocracker reactor to the stripping section of the conventional modular refinery (topping plant) referred as modified modular refinery using Aspen Hysys software, thereby tackling the residual issue associated with modular refinery operations in Nigeria due to inefficient conventional major refineries. The residual percentage value (42.16%) of conventional modular refinery was reduced to 4.92% using the modified modular refinery in Aspen Hysys simulation process and models were developed for the simulation of hydrocracker reactor using five lumps reaction scheme to predict feedstock conversion and products yield along the reactor dimensionless length. To evaluate the developed models, the results were compared against Aspen Hysys software data of the hydrocracker reactor. The percentage absolute error (deviation) of the valuable products light ends, naphtha and diesel showed a close mapping between the model predictions and Aspen Hysys data. Therefore, the models can be reliably used for simulation studies of hydrocracker reactor of the modified modular refinery operations in Nigeria.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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## Nomenclatures

$k_L$ is rate constant for manufacture of light ends

$y_L$ is mass fraction of light ends

$k_N$ is rate constant for recovery of naphtha

$y_N$ is mass fraction of naphtha

$k_D$ is rate constant for recovery of diesel

$y_D$ is mass fraction of diesel

$k_B$ is rate constant for recovery of bottom

$y_B$ is mass fraction of bottom

$\eta$ is catalyst effectiveness factor

$k_i$ is reaction rate constant of specie $i$

$k_0$ is pre-exponential constant

$E_i$ is activation energy of specie

$T$ and $R$ are temperature and gas constant respectively.

$k_{L0}, k_{N0}, k_{D0}$ and $k_{B0}$ are the pre-exponential functions for light end, naphtha, diesel and bottom respectively.

$E_L, E_N, E_D$ and $E_B$ are the activation energies for the production of light end, naphtha, diesel and bottom respectively.

$A$ is hydrocracking reactor area

$\varepsilon$ is voidage value

$v_0$ is volumetric rate

$l_d$ is the dimensionless length

$l$ is dimensional length

$l_r$ is reactor length