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Simulation of Nigerian Crude Oil Types for Modular Refinery (Topping Plant) Operations

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Abstract

This research study focused on the need to curb scarcity and importation of petroleum finished products in oil-producing nation Nigeria through the operation of conventional modular refineries in conjunction with major refineries operating efficiently. Hence, the study focused on the suitability and operations of conventional modular refinery processes by considering twenty different types of Nigerian crude oil for crude oil assay analysis and classification using Aspen Hysys. The crude oil assay results categorized the twenty Nigerian crude oil types as light and medium sweet crude, while based on recovery volume percent at a true boiling point of 370˚C, the twenty crude oil types were categorized into Group A (crude oil with recovery volume above 80%), Group B (crude oil with recovery volume between 70% and 79%) and Group C (crude oil with recovery volume below 70%) respectively. Besides, light and medium sweet oil types were simulated in a conventional modular refinery (topping plant) at different numbers of column trays (25, 29, 35, 40 and 48) to determine their product yield. Based on product yield and equipment costs at different numbers of tray columns, a modular refinery with twenty-nine column trays was applied in this study. Thus, twenty Nigerian crude oil types were simulated in a conventional modular refinery of 30,000 barrel per day capacity and twenty-nine column trays respectively to evaluate their product yield and tray compositions.

Keywords

Topping Plant, Column Tray Number, Products Recovery Volume, Equipment Cost, Simulation, Aspen Hysys

1. Introduction

Crude oil refining involves subjecting the feedstock to a series of physical and chemical processes as a result of which different products are generated. Petroleum refining processes are chemical engineering processes and other facilities used in crude oil refineries (also referred to as oil refineries) to transform crude oil into useful products such as liquefied petroleum gas, gasoline, kerosene, jet fuel, diesel oil and fuel oils [1]. Crude oil refineries are very large industrial complexes that involve many different processing units and auxiliary facilities such as utility units and storage tanks [2]. Each refinery has its own unique arrangement and combination of refining processes largely determined by the refinery location, desired products and economic considerations [3]. In many ways, oil refineries technology is similar to a chemical plant and crude oil feedstock is processed in an oil production plant before refining. There is usually an oil depot (tank farm) at or near an oil refinery for the storage of incoming crude oil feedstock as well as bulk liquid products, and an oil refinery is considered an essential part of the downstream sector of the petroleum industry [4]. Raw or unprocessed crude oil is not generally useful in industrial applications, although light, sweet crude oil (low viscosity, low sulphur) has been used directly as a burner fuel to produce steam for the propulsion of seagoing vessels [5]. The lighter elements, however, form explosive vapours in the fuel tanks and are therefore hazardous, especially in warships. Thus, the different hydrocarbon molecules in crude oil are separated in a refinery operation into components that can be used as fuels, lubricants, and as feedstocks in petrochemical processes that manufacture products such as plastics, detergents, solvents, elastomers and fibers (nylon and polyesters) [6].

Oil refineries are large-scale plants, processing about a hundred thousand to several hundred thousand barrels of crude oil per day. Due to this high capacity, many of the units operate continuously as opposed to processing in batches, at a steady state or nearly steady state for months to years. The high capacity also makes process optimization and advanced process control very desirable [7]. Once crude oil is extracted from the ground, it is transported and refined into petroleum products that have different values. These products are then transported to end-use consumers or retailers. The overall well-to-consumer supply chain for petroleum products is often described as being segmented into three components [8].

1) *Upstream Activities:* This involves exploring crude oil deposits and the production of crude oil. Examples of firms that would belong in the upstream segment of the industry include companies that own rights to drill for oil such as ExxonMobil and companies that provide support services to the drilling segment of the industry such as Halliburton [8].

2) *Midstream Activities:* This involves the distribution of crude oil to refiners, the refining of crude oil into saleable products and the distribution of products to wholesalers and retailers. Examples of firms that would belong in the midstream segment of the industry include companies that transport oil by pipeline, truck or barge such as Oando Plc and companies that refine crude oil such as the

Nigerian National Petroleum Corporation [8].

3) *Downstream Activities*: This involves the retail sale of petroleum products. Gasoline stations commonly referred to as filling or petrol stations in Nigeria are perhaps the most visible downstream companies, but companies that deliver heating oil or propane would also fall into this category [8].

Crude oil is essentially a mixture of many different hydrocarbons, all of varying compositions and complexities. The integral part of an oil well development plan is essentially the requirement of forecasting the performance of oil wells in a reservoir or in the entire field [9]. In order to separate the crude oil into different components that make up the raw natural resource, crude oil must be refined (refinery process) so that components can be removed according to their temperature difference (Boiling points) [10]. Thus, the Nigeria government owns and operates four major refineries through the Nigerian National Petroleum Corporation (NNPC) namely, the 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 their original capacities [11] [12]. Therefore, the dependency on the importation of petroleum products in Africa's largest crude oil producer, Nigeria has led to an incessant and continual scarcity of petroleum products. In addition, illegal refineries that feed on stolen crude oil abound in Nigeria with associated operational and production hazards such as environmental pollution, crude oil theft, fire safety risk and poor quality petroleum products, etc. [13]. To curb the incessant and continual scarcity of petroleum products, and environmental hazards associated with illegal (local) refineries, and reduce to minimal the importation of petroleum products, the existing refineries must be revamped and operated at full capacity, while new refineries are built by partnering with private sector thereby leading to deregulation of the sector [14]. Since the construction of major refineries is 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 their associated environmental hazards [15] [16] [17].

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 [10]. The components of a modular refinery include tankage, a distillation unit, facilities for gas recovery, 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 determine 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) [18]. Topping refineries are hastily becoming a viable, flexible and cost-effective scheme for petroleum producers especially where there is a quick requirement to meet local needs of crude oil products with relatively low investment cost, speed and construction period are some of the major advantages of a modular refinery [19]. Hence, this research study focused on the classification of Nigeria crude oil types as effective feedstocks for modular refinery operations, simulation of the classified crude oil types in the modular refinery (Topping plant) of different column tray numbers (25, 29, 35, 40 and 48), thereby proposing a column tray number for this study based on products yield and equipment cost using Aspen Hysys.

2. Materials and Method

The materials applied in this research study include twenty different types of Nigerian crude oil, API values, Watson characterization factor, sulphur content, modular (topping plant) refinery, Aspen Hysys Version 10, etc. Thus, the following procedures are applied in performing this research study.

2.1. Crude Oil Assay

This research study involved crude oil assay analysis on twenty different types of Nigerian crude oil from different oil fields using Aspen Hysys Version 10 to determine their compositions, properties, product cuts and ascertain their suitability as feedstock for modular refinery (topping plant). Thus, crude oil assay consists of a compilation of data on properties and composition of crude oils. The assay provides critical information on the suitability of crude oil for a particular refinery and estimating the desired product yields and quality. It also indicates how extensively a given crude oil should be treated in a refinery to produce fuels that are in compliance with environmental regulations. A crude oil assay include the following major specifications: 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, Watson characterization factor. Thus, these parameters are evaluated and used in determining the nature or grade of the crude oil type (light, medium, heavy, sweet and sour crude). In addition, the results of crude oil assay analysis showed general information about the crude, weight percentage of pure crude components, crude properties and true boiling point distillation.

2.2. Crude Oil Classification

Besides, the twenty Nigeria crude oil types were classified after crude oil assay analysis based on products recovery temperature range and products cut fractions.

2.3. Modular Refinery (Topping Plant) Process

The number of trays or plates in the crude distillation unit of the modular (topping plant) refinery shown in **Figure 1** was varied to study trays effect on overall

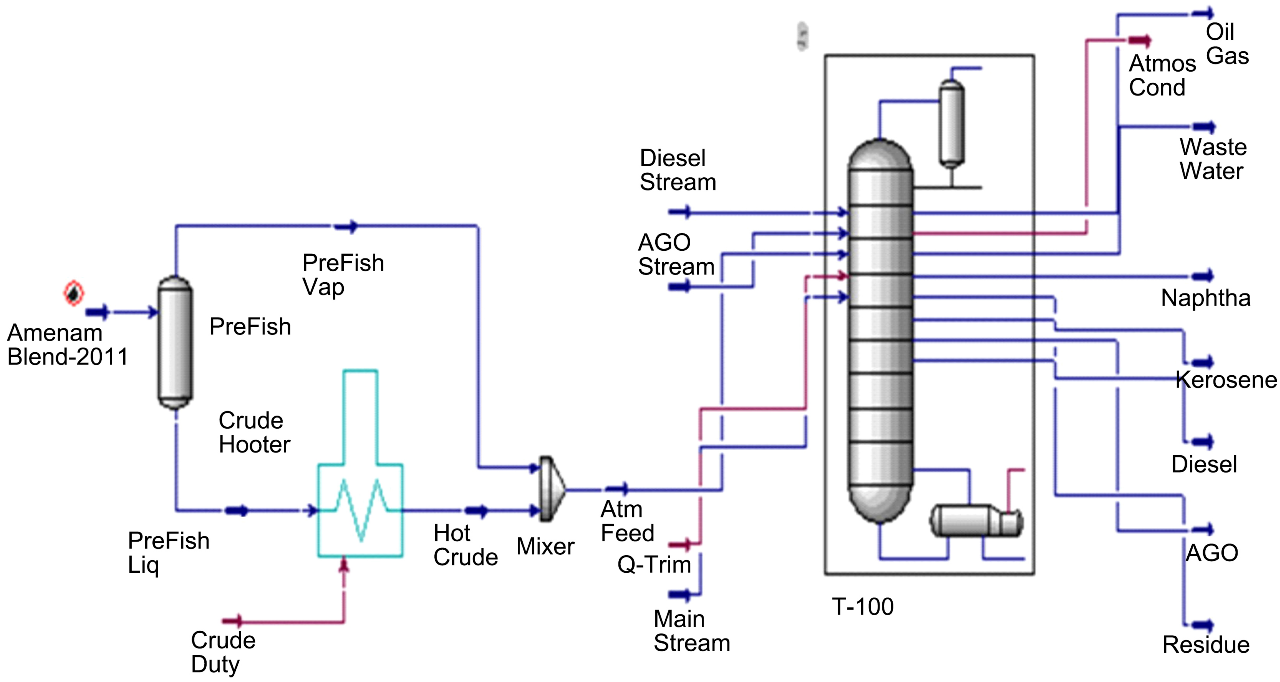

Figure 1. 30,000 BPD capacity modular refinery.

products yield, equipments cost and products tray compositions. Thus, column tray numbers of twenty-five, twenty-nine, thirty-five, forty and forty-eight were applied in the crude distillation column of the modular refinery in this study to simulate each of the classified light sweet (Akpo Blend 2011 with API of 46.70) and medium sweet (Okoro 2012 with API of 23.54) crude oil types. The maximum tray number of 48 was applied in this study based on the column tray number of the Port Harcourt refinery crude distillation unit. The simulation processes were carried out for crude oil on the basis of 30,000 barrel per day (902.1 Kgmol/hr).

2.4. Proposed Modular Refinery Simulation

The Aspen Hysys modeled 30,000BPD capacity modular refinery shown in Figure 1 was used to simulate twenty different types of Nigeria crude oil into product components (Off gas, Naphtha, Kerosene, diesel, Atmospheric gas oil and Residue) in a crude distillation column of 29 numbers of trays. This column tray number was chosen for the study based on products yield and equipment costs.

3. Results and Discussion

The results of the research study are highlighted thus.

3.1. Crude Oil Analysis and Classification

The results of the crude oil assay analysis carried out on twenty Nigerian crude oil types using Aspen Hysys comprises of the crude oil general information (crude name, oil field, location, assay ID, etc.), pure components weight percent, crude oil properties (API, sulphur content, kinematic viscosity at 50˚C, 100˚C, 150˚C, nitrogen, vanadium, nickel, asphaltenes, Watson characterization factor, wax content, total acid number and pour point) and true boiling point distillation. Therefore, these Nigerian crude oil types were classified as shown in **Table 1** as light and medium sweet crude, and based on the crude oil API value and sulphur content weight percent, its categorization was depicted in **Figure 2** and **Figure 3** respectively. In addition, based on the crude oil recovery volume and residual percentages at process temperature of 370˚C, the classified Nigerian crude oil types were grouped into three.

Table 1. Classification of Nigeria crude oil types.

S/N	Crude Oil Type	Classification
1	Agbami 2012	Light Sweet Crude
2	Akpo Blend 2011	Light Sweet Crude
3	Akpo 2014	Light Sweet Crude
4	Amenam Blend 2011	Light Sweet Crude
5	Nigeria Brass 2012	Light Sweet Crude
6	Oso Condensate 2016	Light Sweet Crude
7	Bonny Light 2011	Medium Sweet Crude
8	Brass River 2011	Medium Sweet Crude
9	Erha 2012	Medium Sweet Crude
10	Forcados Blend 2014	Medium Sweet Crude
11	Nigeria Brass 2015	Medium Sweet Crude
12	Okwori 2011	Medium Sweet Crude
13	Okwuibome 2014	Medium Sweet Crude
14	Qua Iboe 2012	Medium Sweet Crude
15	Bonga 2012	Medium Sweet Crude
16.	Okoro 2012	Medium Sweet Crude
17	Nigeria Forcados 2012	Medium Sweet Crude
18	Bonga 2014	Medium Sweet Crude
19	Usan 2013	Medium Sweet Crude
20	Usan 2015	Medium Sweet Crude

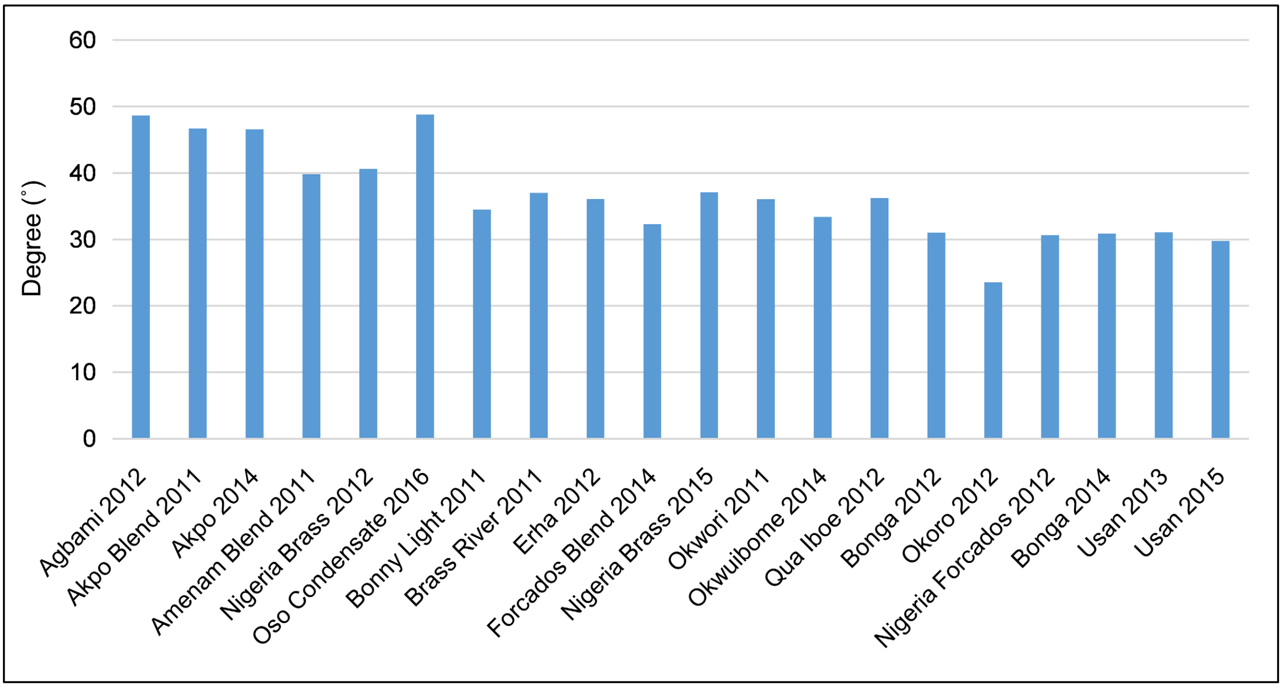

Figure 2. API values of Nigerian crude oil types.

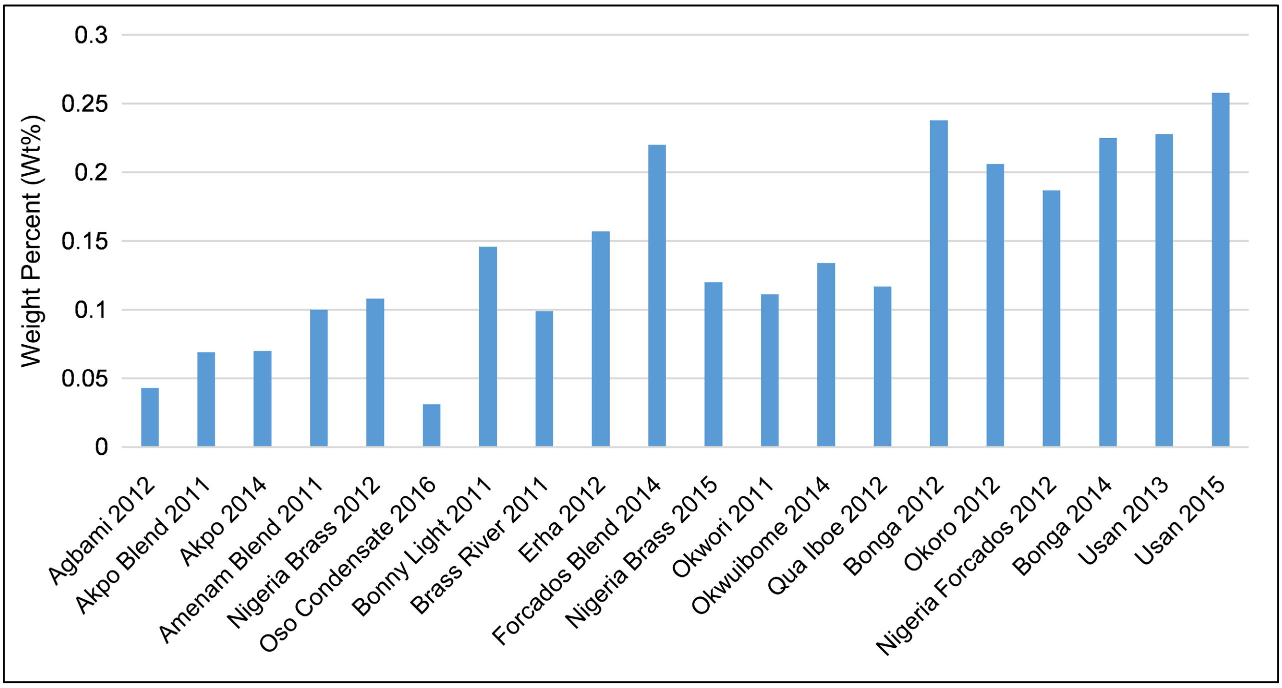

Figure 3. Sulphur contents weight percent of Nigerian crude oil types.

3.2. Group A Nigerian Crude Oil Types

Group A Nigerian crude oil types referred to crude oil with high recovery volume of eighty percent (80%) and above and relatively low sulphur contents below 20% as shown in **Figure 4** and **Figure 5** respectively. These Nigerian crude oil types include Nigerian Brass 2012, Brass River 2011, Oso Condensate 2016, Agbami 2012, Erha 2012, Akpo 2014, Akpo Blend 2011 and Forcados Blend 2014.

3.3. Group B Nigerian Crude Oil Types

Also, Nigerian crude oil types with recovery volume percent between 70 and 79 and residual percent less than 30% are categorised as Group B as shown in Figure 6 and Figure 7 respectively. The group B Nigeria crude oil types are Nigerian Brass 2015, Okwori 2011, Amenam Blend 2011, Bonny Light 2011 and Qua Iboe 2012.

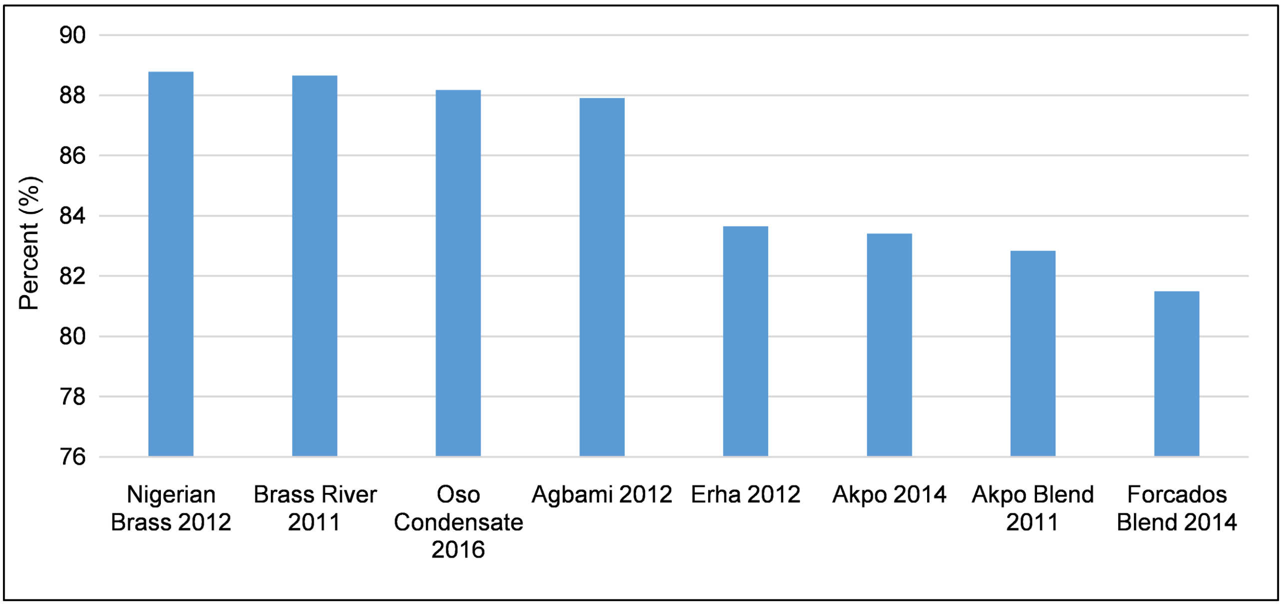

Figure 4. Group A Nigerian crude oil types recovery volume.

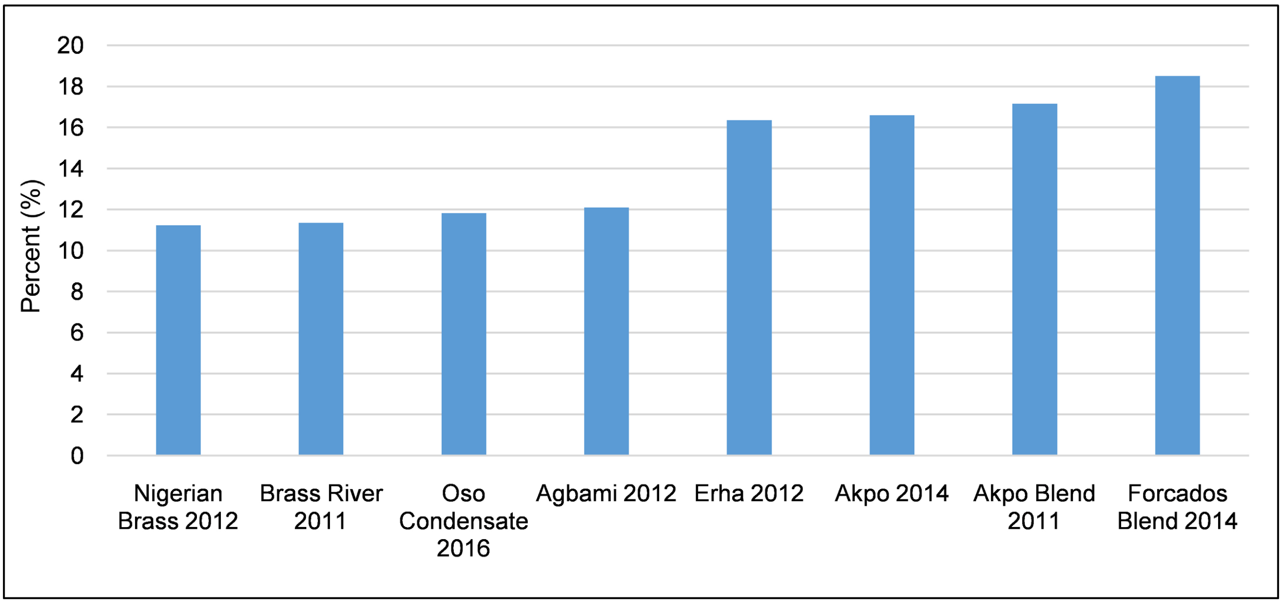

Figure 5. Group A Nigerian crude oil types residual percent.

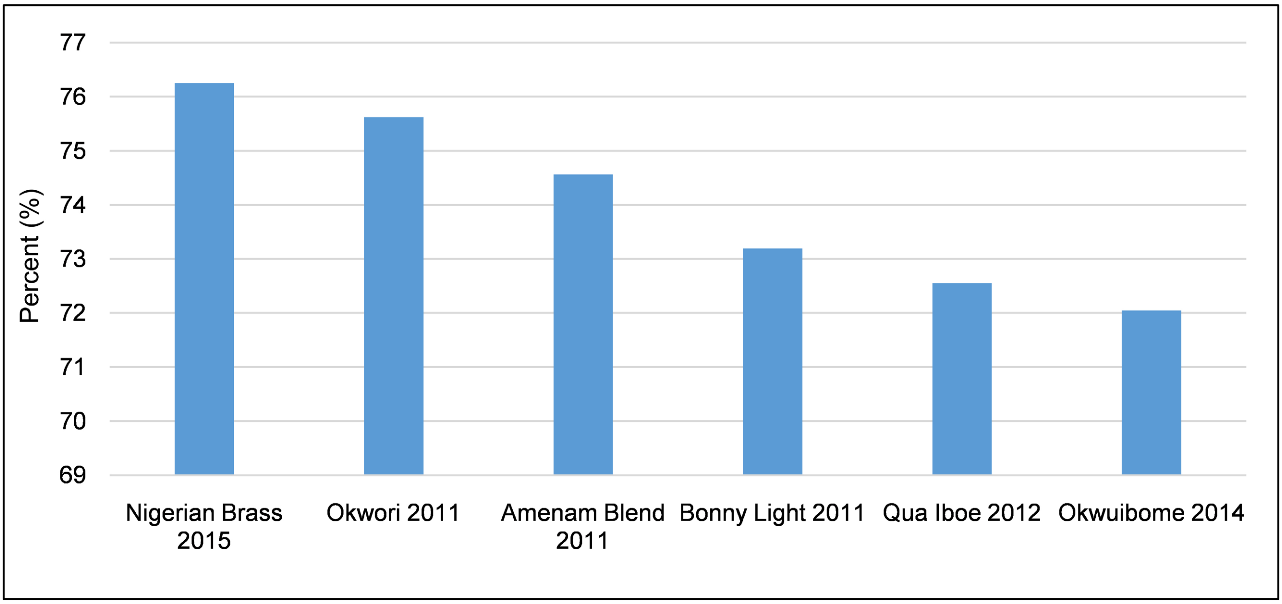

Figure 6. Group B Nigerian crude oil types recovery volume.

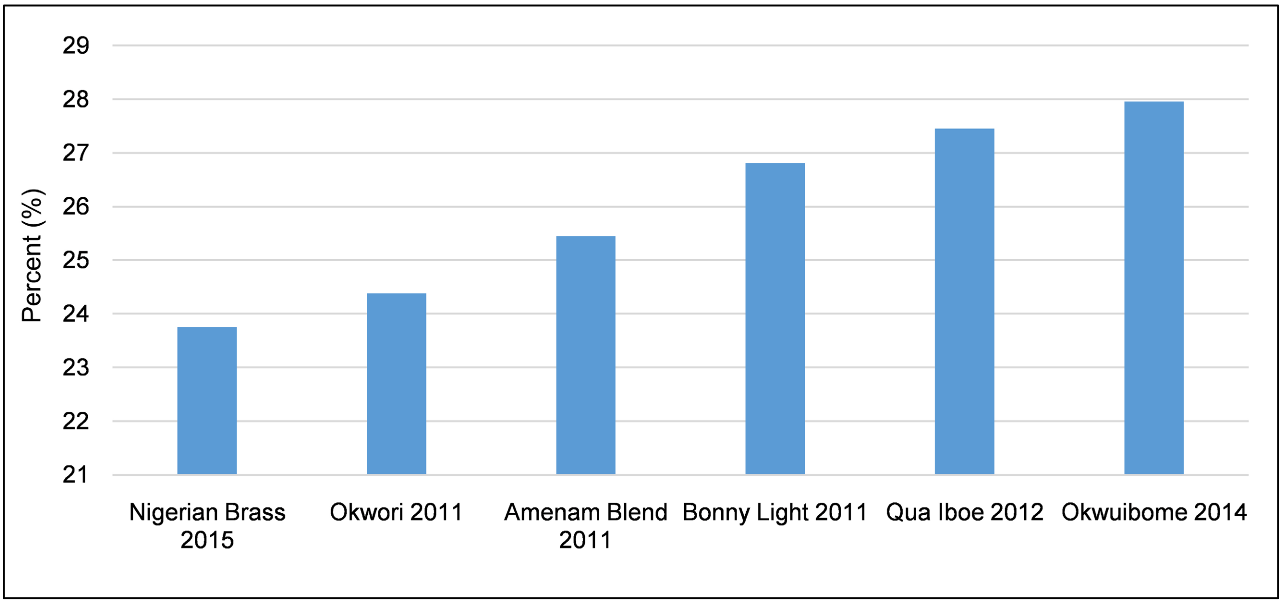

Figure 7. Group B Nigerian crude oil types residual percent.

3.4. Group C Nigerian Crude Oil Types

Besides, Nigerian crude oil types with percentage recovery volume below 70% and residual percentages of 30% and above are categorised as Group C as shown in Figure 8 and Figure 9 respectively. These crude oil types include Nigerian Forcados 2012, Bonga 2012, Bonga 2014, Usan 2013, Usan 2015 and Okoro 2012.

3.5. Modular Refinery Simulation at Different Tray Numbers

The results of modular refinery simulations at different number of trays or plates in the crude distillation unit for Akpo Blend 2011 with API of 46.70 and Okoro

2012 with API of 23.54 are depicted in **Table 2** and **Table 3** respectively.

Furthermore, cost analysis of the topping plant equipments were carried out using Aspen Hysys at different number of trays of the conventional modular refinery, since the size (height and diameter) and cost of the crude distillation unit is evaluated by the number of trays or plates in the column. Thus, **Table 4** depicted equipments cost for light sweet crude (Akpo Blend 2011) and medium sweet crude (Okoro 2012) at different column tray numbers respectively. Hence, the equipments cost at a given column tray number is higher in Okoro 2012 than in Akpo Blend 2011 owing to the heat duty cost of Okoro 2012 due to its

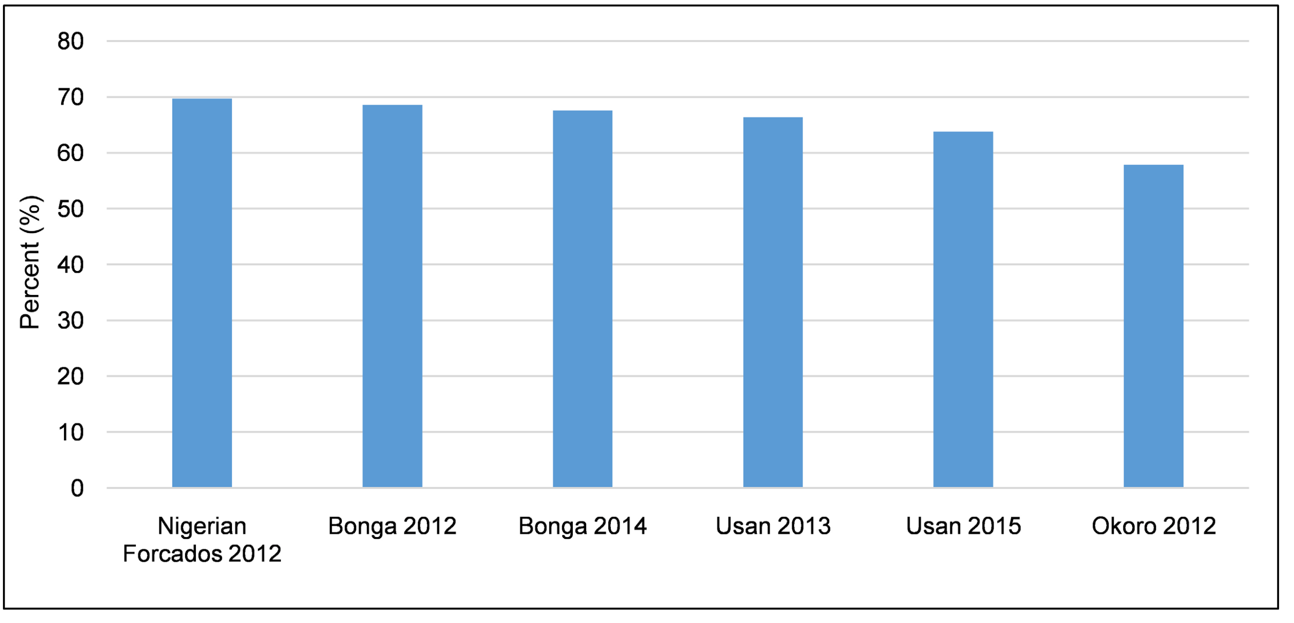

Figure 8. Group C Nigerian crude oil types recovery volume.

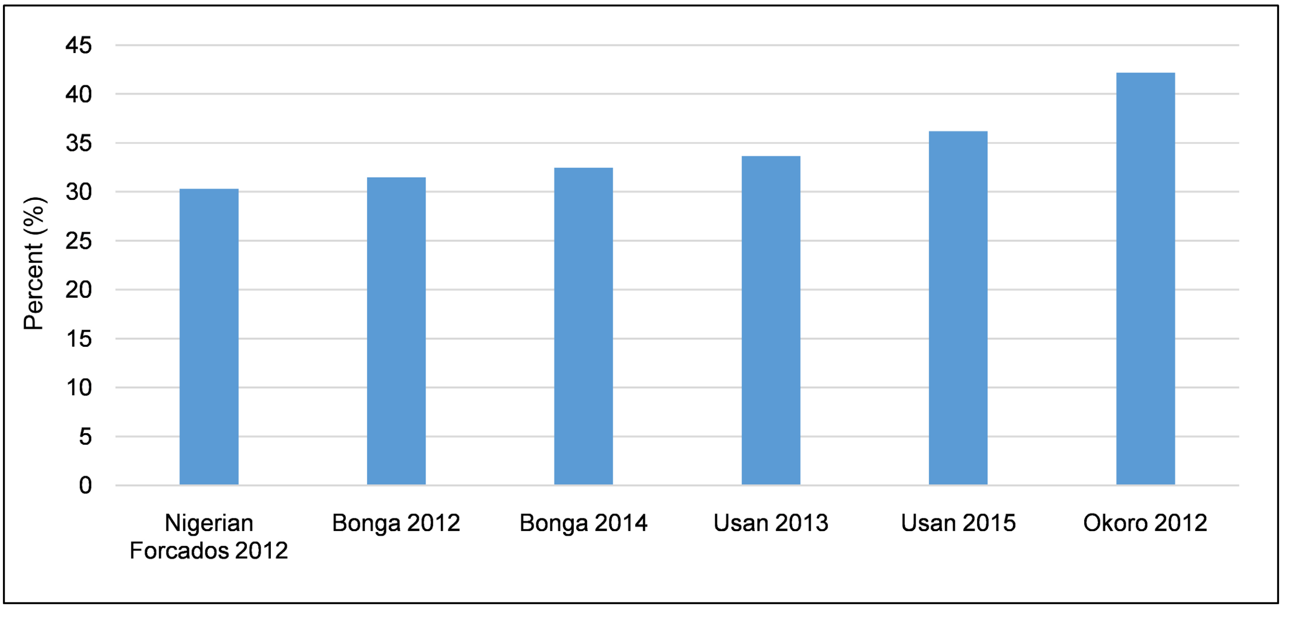

Figure 9. Group C Nigerian crude oil types residual percent.

Table 2. Products yield of Akpo blend 2011 at different column tray numbers.

Products Yield (Kgmol/hr)	Crude Distillation Column at Different Tray Numbers				
	25	29	35	40	48
Off Gas	0.000010186	0.00003	0.00002986	0.00003078	0.00003067
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 3. Products yield of Okoro 2012 at different column tray numbers.

Products Yield (Kgmol/hr)	Crude Distillation Column at Different Tray Numbers				
	25	29	35	40	48
Off Gas	0.00002267	0.00002102	0.0003836	0.0003787	0.0003787
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

Table 4. Equipment cost at various tray numbers.

Column Tray Number	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

low API value, which is a medium sweet crude. Hence, based on products yield and equipments cost analysis, crude distillation column with twenty-nine number of trays was proposed and applied in this study.

3.6. Modular Refinery Products Tray Composition

The twenty Nigerian crude oil types were simulated in a 30,000 barrel per day (902.1 Kgmol/hr) capacity conventional modular (topping plant) refinery of twenty-nine trays or plates in the crude distillation unit to determine their products compositions at each tray of the column. Thus, the maximum and minimum products yield or compositions of each crude oil type at their respective tray number are deduced. Therefore, the products yield or composition of sweet light and medium crude oil type of Agbami 2012, Akpo 2014, Amenam Blend 2011, Bonga 2012 and Okoro 2012 are shown in Figures 10-14 respectively.

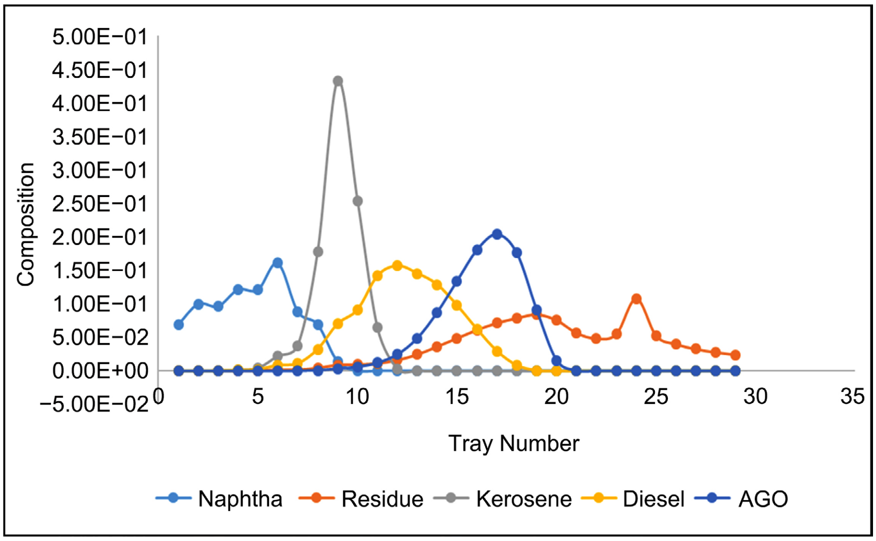

Figure 10. Products tray composition of Agbami 2012.

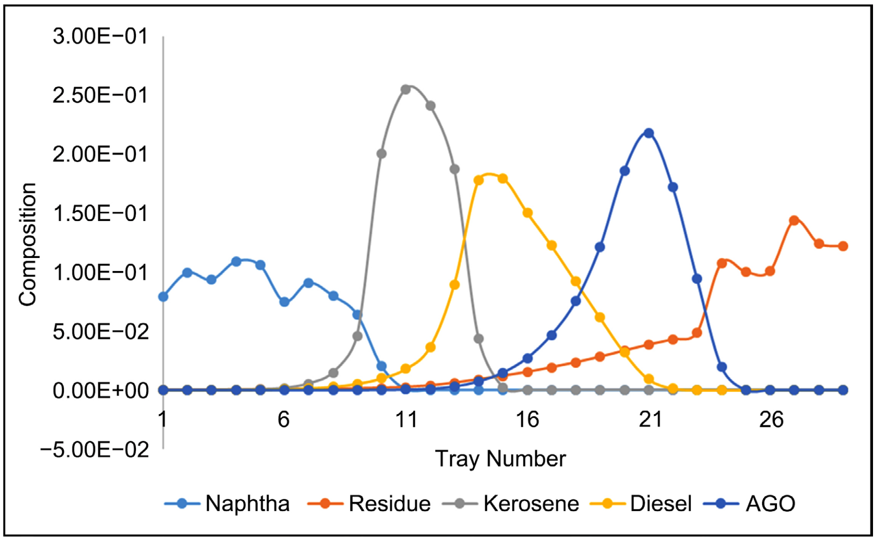

Figure 11. Products tray compositions of Akpo 2014.

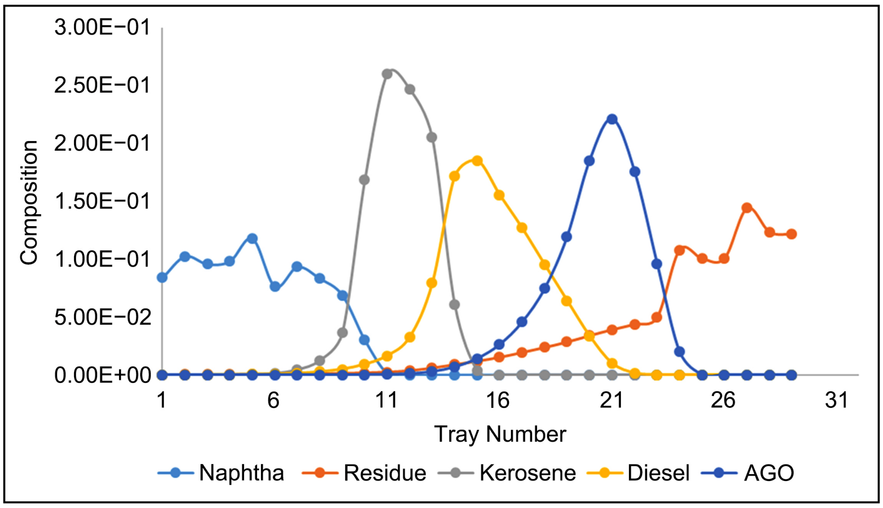

Figure 12. Products tray compositions of Amenam Blend 2011.

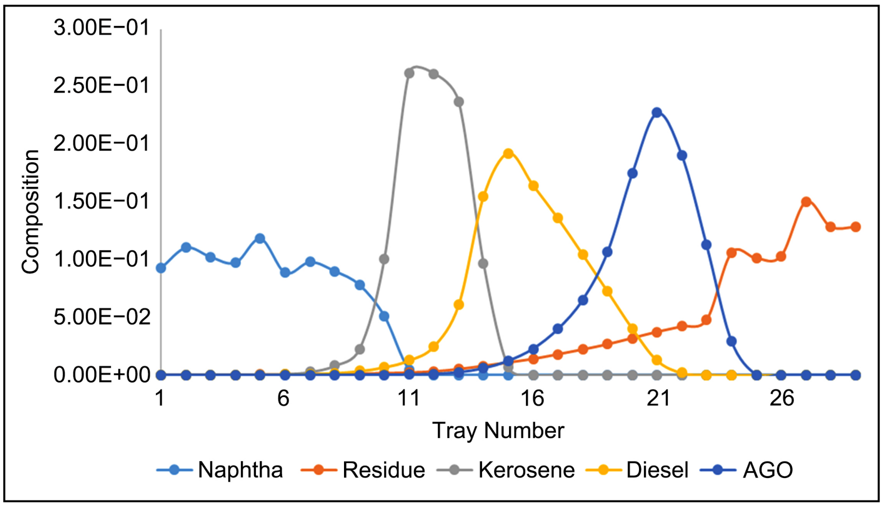

Figure 13. Products tray compositions of Bonga 2012.

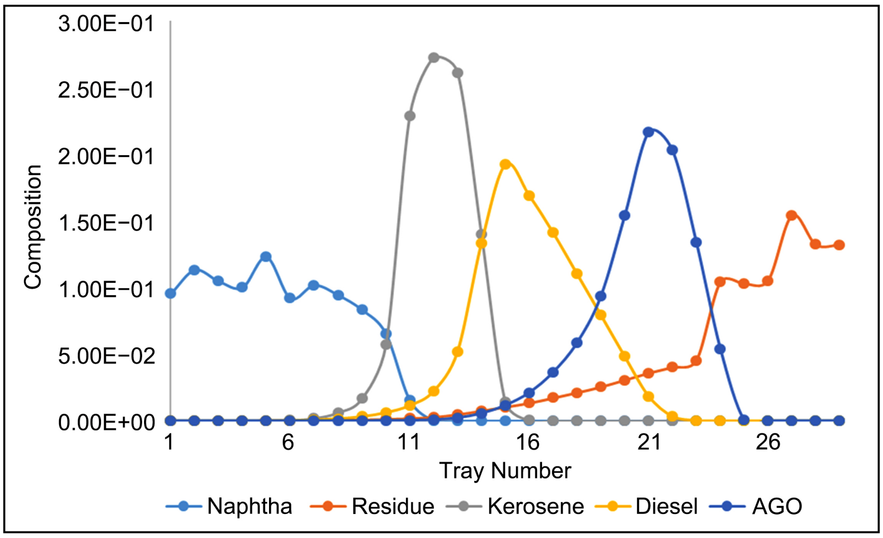

Figure 14. Products tray compositions of Okoro 2012.

4. Conclusion

Twenty different types of Nigerian crude oil were analysed and classified for conventional modular refinery operations in Nigeria as a panacea to reduce petroleum finished products scarcity and importation. The analysis of the crude oil types (crude oil assay and characterization) was carried out using Aspen Hysys, and the results shown above reviewed that most Nigerian crude oil types are light and medium sweet crude oil. Also, the Nigerian crude oil types were grouped into three based on their recovery volume and residual percent before their simulations in a modular refinery of 30,000 bpd capacity. The classified crude oil types were simulated with a modular refinery (topping plant) at different tray numbers (25, 29, 35, 40 and 48) of the crude distillation unit to study product yield and equipment cost analysis using Aspen Hysys. Based on the result of these analyses, a conventional modular refinery with twenty-nine trays in the crude distillation unit was chosen for the simulation. Thus, twenty Nigerian crude oil types were simulated with a conventional modular refinery of twenty-nine trays in the crude distillation column to determine product composition (maximum and minimum) on each tray of the column. Besides, due to high residual percentages of Group B and C Nigerian crude oil types, this research study recommended further processing techniques to convert the high percent residue to more valuable products.

Conflicts of Interest

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

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