RESEARCH ARTICLE OPEN ACCESS

Effect of Crude Assay on Distillate Cuts Yield in Batch Distillation of Crude Oil

Raphael Tari Samuel*,[1], Joseph Alah*,[2], Rhoda H. Gumus*,[3], Goddey Oyaenene John*,[4]
**(Department of Chemical Engineering, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria)*
[1](Email: raphael.samuel@ndu.edu.ng), [2](Email: josephalah@ndu.edu.ng), [3](Email: rhodagumus@ndu.edu.ng), [4](Email: johngoddey0@gmail.com)

ABSTRACT
Establishing modular refineries near oil-bearing areas is a key policy initiative of the Nigerian government to increase local refining capacity and reduce or eradicate the perennial shortage of petroleum products in the country. Modular refineries are less complex and cheaper to build and maintain, compared to conventional refineries. To further reduce complexity, cost, and make in-country design, construction, and operation possible, modular mini refining plants using batch distillation units have been proposed. This has made it necessary to carry out systematic studies in-mini batch processing of crude oil. This paper investigates the effect of crude oil assay on distillate cuts yield in a mini-batch distillation plant using a process simulator. The simulation was carried out with three Nigerian crude oils (Bonny Light, Brass River, and Forcados) under the same operating conditions to reveal and analyze the volumetric yield of the different distillate cuts. The results show that the different crudes favoured the production of different cuts. Bonny Light gave the highest total cuts yield of 61.22% compared to Forcados (54.38%) and Brass River (55.45%). The results from this study will help investors to determine the economic viability of building mini modular refining plants with batch fractionating units.

***Keywords* –** Aspen plus, Batch distillation, Crude assay, Modular refinery, Simulation

Date of Submission: 26-03-2021 Date of Acceptance: 09-04-2021

I. INTRODUCTION

Distillation is a physical process for separating the components of a liquid mixture based on their relative volatilities. From an equipment standpoint, distillation is carried out in multiple stages in vapour/liquid contact devices (e.g. trays, sieves and packing). It is the most widely practiced separation method in the chemical, petroleum and related process industries. According to Kister [1], the superiority of distillation for separating fluid mixtures is so fundamental that it is unlikely to be displaced. In petroleum refining, crude oil assay data play a very important role in the crude distillation process.

Crude oil assay is a compilation of physical and chemical data that uniquely describe or characterize crude oils. Although the elementary composition usually falls within a relatively narrow range, no two crude oils are identical. There are crucial differences in crude oil quality as each crude oil has unique molecular and chemical characteristics. Typically, small changes in composition can greatly affect the physical properties of crude oil and the level of processing required to give marketable products. In particular, variation in crude oil characteristics affects the design of the distillation column and the distillation outcome, including the amount and quality of the products produced. Hence, crude oil assay data help refiners determine if a crude oil feedstock is compatible with a particular petroleum refinery or is likely to cause yield, quality, production, and environmental problems [2].

Based on the mode of operation, distillation can be classified into two main categories: continuous distillation and batch distillation. In continuous distillation, the feed is fed continuously into the distillation column and the distillation products (e.g. distillates, bottoms, side streams) are continuously removed from the column without interruptions except there is a problem in the operation. This mode of distillation is capable of handling high throughputs and accommodates multiple feed streams and multiple product drawing points. Essentially, continuous distillation is a steady state operation and is the most commonly used mode of distillation in the petroleum and chemical industries.

On the other hand, batch distillation is distillation carried out in batches. That is, the reboiler or pot is charged with the feed and distilled completely before recharged again with fresh feed. Batch distillation has always been an important part of the production of seasonal or low capacity and high-purity chemicals and is very suitable for today's frequently changing product specification requirements and market demand. Batch distillation is also very flexible; several types of mixtures can be handled by switching the operation condition of the column [3] and several components can be separated with only one column [4]. Thus, batch distillation can cope with uncertainties in feed and product specification.

Furthermore, batch distillation often means simpler operation and lower capital cost than continuous distillation [5]. Although batch distillation is used more frequently in the pharmaceutical, biochemical and specialty chemical industries [6], its competitiveness in the chemical industry has increased in recent years [7]. This can also be linked to the recent trend of building small, flexible plants that are close to market consumption [8]. Unlike continuous distillation, batch distillation is a time-varying process because the composition of the higher boiling point component increases in concentration over time. Nonetheless, current technology has made the simulation of batch distillation, or other batch processes, much easier and less complicated.

1.1. Motivation for the Study

In recent years, the Nigerian government has issued licenses to several private investors to build modular refineries in the Niger Delta geopolitical region, close to marginal oil fields, in the face of the suboptimal performance of the existing four conventional refineries in the country. This is aimed at making refined products readily available for local consumption and to substantially curtail or eradicate the perennial shortage of petroleum products in the country which has necessitated the importation of petroleum products with the attendant loss in foreign exchange earnings. Although building a modular refinery is far cheaper than building a conventional refinery, the cost is still beyond what many indigenous investors can afford if continuous distillation is employed. Continuous distillation increases the number of components, instrumentation, and controls required to run the modular plant efficiently and safely. Hence, it has been opined that it would be much better to build small capacity modular refining plants (i.e. modular mini refining plants) and employ the batch distillation mode in such plants [17].

Adopting batch distillation will reduce the design burden, complexity, and the cost of construction so that such plants can be easily designed, constructed and operated locally. This will make building and operating modular refineries attractive and affordable to local investors. It is therefore necessary to carry out systematic scientific studies in batch distillation of crude oil in a mini refining plant.

A study by How [9] described the simulation of a batch distillation unit to validate experimental results using Aspen Batch Distillation (ABD). Maulidda [10] modeled a mini plant ethanol-water batch distillation column based on component mass balance, vapor-liquid equilibrium and other physical characteristics representing the dynamics of the batch distillation column. The models were simulated in Matlab with real parameter values and validated with experiments. Alvarez *et al*. [11] evaluated the batch distillation process in ethanol production using Aspen Plus in both plate and packed columns to verify the effectiveness of the calculations for the batch distillation process for recovering ethanol. However, the feeds used for these studies were binary mixtures. Hence, they are less complex compared to crude oil which is a multi-component mixture. Some simulation studies on crude oil distillation units using Aspen Hysys [12,13] and Aspen Plus [14,15,16] have also been reported. Nevertheless, these studies were based on continuous distillation columns. There is hardly any recent published research work on batch distillation of crude oil in the open literature. This may not be unconnected with the association of continuous distillation with conventional refineries due to the high throughput and complexity of these facilities.

1.2. Aim and Objectives

The aim of this paper is to investigate the effect of crude oil assay on distillate cuts yield in a batch distillation unit. The objectives include determining the distillates yield of three different crudes under the same operating conditions, analyzing the temperature and liquid volume profiles in the pot as well as the component holdup in the distillate receivers over time. The results obtained from this study will help in developing investment analysis of a modular mini refining plant adopting the batch distillation mode.

II. METHODOLOGY

2.1. Process Equipment

Fig. 1 shows the setup of the conventional batch distillation system (batch rectifier) that was simulated. It consists of the following equipment:

- *Still pot or reboiler:* for heating the crude oil.
- *Tray column (batch rectifier):* for vapour liquid equilibrium.
- *Condenser (water-cooled):* for cooling the vapour.

- *Reflux drum:* to provide reflux through the top of the column.
- *Receivers:* to serve as accumulative recipients for products (main cuts) and off cuts also known as mixtures or slops.

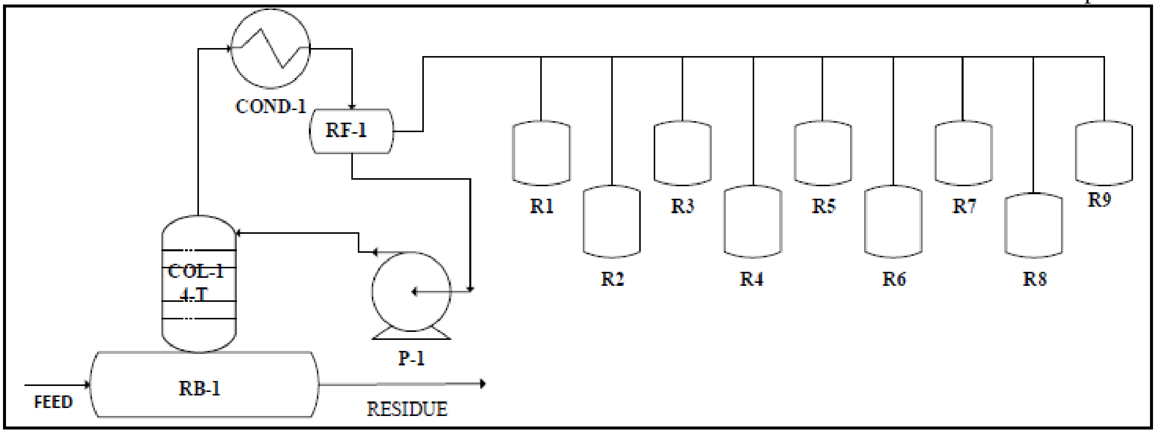

Figure 1: Batch distillation column with five receivers (R1, R3, R5, R7 and R9) for main cuts and four receivers (R2, R4, R6 and R8) for off cuts.

2. 2. Simulation Data

TABLE 1 shows the properties of the crudes investigated while the feed data and the configuration parameters of the column used for the simulation are presented in TABLES 2 and 3 respectively.

Table 1: Crude Oil Properties

Crude Name	API	Density at 15 °C, kg/m^3	Viscosity, CST at 10 °C	Viscosity, CST at 50 °C
Bonny Light	35.09	849.0	8.7	2.9
Brass River	40.10	824.4	3.2	1.6
Forcados	31.50	867.5	11.4	3.5

Table 2: Feed Data of Crude Oil

Temperature = 25 °C
Pressure = 1atm
Initial feed volume = 250 litres
Property method = Peng-Robinson

Component	Mole fraction (%)
Bonny light crude oil	1
Brass crude oil	1
Forcados crude oil	1

2.3. Process Description

A conventional batch distillation configuration with constant reflux was used to process the three crudes investigated using the same operating conditions. Firstly, the reboiler or still pot is charged with 250 litres of the feed and heated continuously. The vapour generated is then directed to the condenser and the condensate is collected intermittently in receivers either as products (main cuts) or slops (also called mixture or offcuts), which are recycled to the reboiler until the distillation is complete. When the distillation is complete, the heat is shut off, the residue left in the pot is removed and the reboiler is charged with fresh feed.

Table 3: Batch Distillation Column Configuration Parameters

Property	Value
Pot diameter	0.5m
Pot horizontal length	2.4m
Number of stages	6
Condenser type	Total
Reflux ratio	2.5
Length of reflux drum	0.5m
Diameter of reflux drum	0.5m
Type of tray	Sieve
Hole diameter of the tray	15mm
Tray diameter	0.4m
Tray spacing	0.35m
Efficiency	1deal

2.4. Simulation Procedure

All the simulations were carried out using the Aspen Plus simulation software using the procedure presented in Fig. 2.

III. RESULTS AND DISCUSSION

3.1. Distillate Cuts Yield

The volumetric yield of the different cuts obtained from fractionating 250 litres of crude oil for the three crudes simulated is presented in Fig. 3. The result shows that Bonny Light favoured the production of off gas giving a yield of 10.71 litres compared to Brass River (7.22 litres) and Forcados (1.87 litres). When expressed in percentage form, these volumes correspond to 4.28, 2.89 and 0.75 volume percent for Bonny Light, Brass River and Forcados respectively.

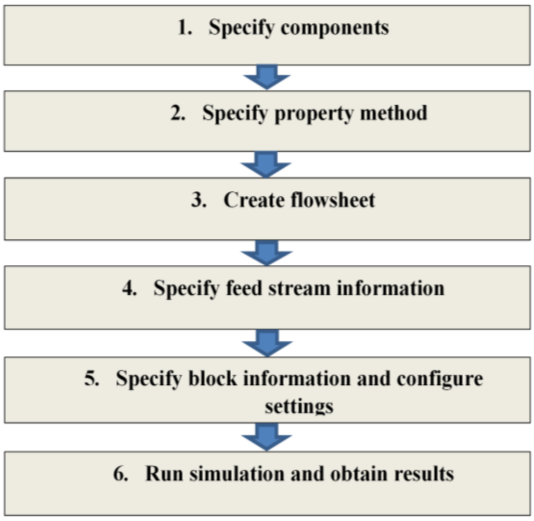

Figure 2: Simulation procedure

For Naphtha, the amounts produced were 43.28, 18.73 and 56.33 litres for Bonny Light, Forcados and Brass River respectively. These correspond to 17.31, 7.49 and 22.53 volume percent for Bonny Light, Forcados and Brass River respectively. Thus, Brass River produced the highest volume of Naphtha. The result for kerosene shows that 28.86, 32.30 and 26.17 litres were produced by Bonny Light, Brass River, and Forcados respectively. The corresponding percentages are Bonny Light (11.54%), Brass River (12.92%) and Forcados (10.47%). Thus, Brass River gave the highest volume of kerosene produced.

The amount of Diesel produced was 47.44, 36.14 and 60.96 litres for Bonny Light, Brass River, and Forcados respectively which correspond to 18.97% (Bonny), 14.55% (Brass River) and 24.38% (Forcados). In other words, Forcados crude oil produced the highest amount of Diesel.

In the case of AGO, the yield was 22.77, 6.63 and 28.22 litres for Bonny Light, Brass River and Forcados respectively which amounts to Bonny Light (9.11%), Brass River (2.65%) and Forcados (11.29%). Thus, Forcados produced the highest volume of AGO. The amount of Residue produced shows 48.96, 54.47 and 57.91 for Bonny Light, Brass River and Forcados respectively amounting to 19.58% for Bonny Light, 21.79% for Brass River and 23.16% for Forcados. This means Forcados crude oil gave the highest volume of residue from the simulation. This is understandable as Forcados is the heaviest of the three crude oils simulated in this study.

In general, the lighter crudes produced higher yields of the lighter cuts while the heaviest crude produced more of the heavier cuts and residue. In particular, Bonny Light favoured the production of off gas, Brass River favoured the production of naphtha and kerosene, while Forcados (the heaviest crude) favoured the production of diesel and AGO. Notably, Bonny Light with an API gravity of 35.09 is considered to be heavier than Brass River with an API gravity of 40.10. However, Bonny Light produced a lower volume of residue than Brass River due to its relatively higher yields of off gas and diesel. This implies that there may be need to determine and adopt the configuration of the distillation system in some cases to maximise the yield of the more desired refined products for any given crude oil.

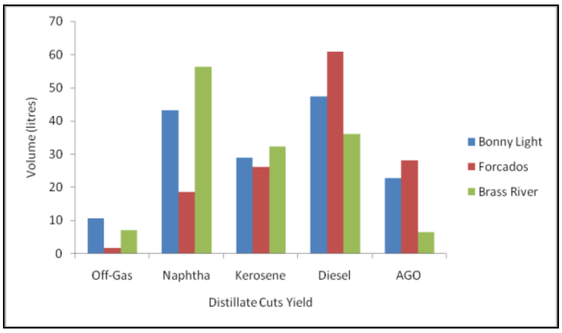

Figure 3: Simulation results showing distillate cuts yield in Bonny Light, Forcados and Brass River

3.2. Pot Temperature-Time Profile

Fig. 4 shows the temperature profile within the still pot or reboiler with time. The increase in temperature in the pot with time is obvious because there was continuous heat input over time. Forcados which is the heaviest of the three crudes evidently required higher distillation temperatures than the others hence it consistently showed the highest temperatures compared to the other crudes. On the other hand, Bonny Light and Brass River that have API gravities that are closer to each other have similar temperature profiles.

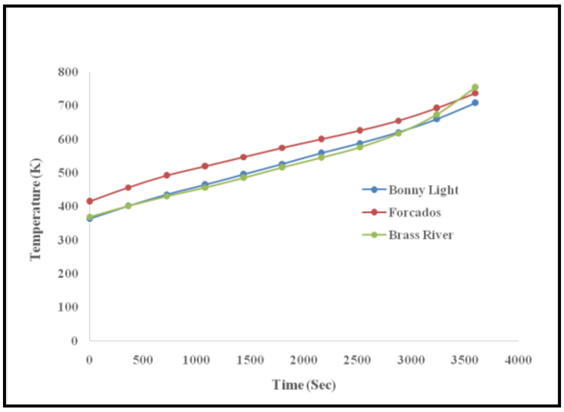

Figure 4: Pot Temperature-time profile of the simulated crudes

3.3. Pot Liquid Volume -Time Profile

Figure 5 shows the liquid volume of the still pot as a function of time for the three crudes investigated. In general, the initial liquid charge decreases as time increases. This is expected because the components initially present in the liquid are removed in the form of the various products (distillate cuts) with time. The volume reduction was fastest with Brass River (the lightest). Since its rate of distillation is faster, more distillates leave the pot. Hence, its volume in the pot also reduces faster. For Forcados, the volume in the pot is higher initially because distillates produced were low at lower temperatures. However, when the distillates volume increased with increasing temperature, the volume in the pot also reduced accordingly. Similar reasoning applies to the pot volume profile for Bonny Light.

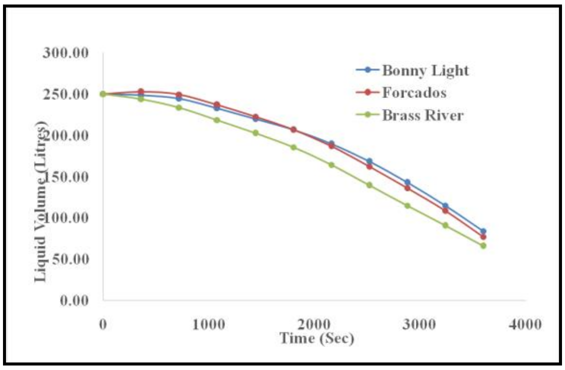

Figure 5: Pot Liquid Volume -Time profile of the simulated crudes

3.4. Component Holdup in the Distillate Receivers

The holdup of the distillates (pseudo components) in the nine receivers as a function of time is presented in this section. Figs. 6 to 14 show the results for Bonny Light only. The results show the time at which each cut was obtained. As expected, the lighter cuts were received earlier than the heavier cuts. In particular, the simulation results for the different crudes vary in terms of the time, total mass holdup, as well as in the components and temperatures obtained. In other words, although similar products were obtained from the simulated crudes, the time products were obtained and the holdups of the fractions associated with these times were different for the different crudes which can be related to the property of the different crudes based on their assays.

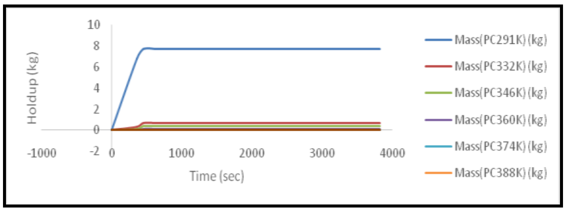

Figure 6: Distillate Receiver 1; LPG Mass Hold Up

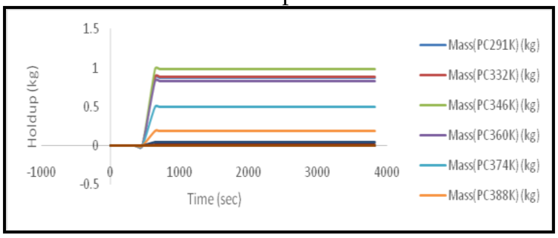

Figure 7: Distillate Receiver 2; LPG-Naphtha Slop Mass Hold Up

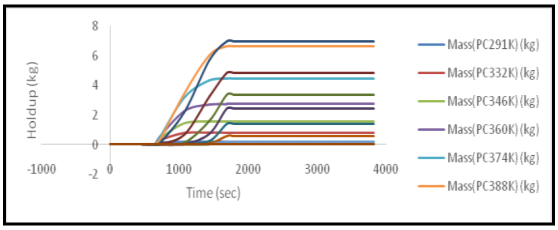

Figure 8: Distillate Receiver 3; Naphtha Mass Hold Up

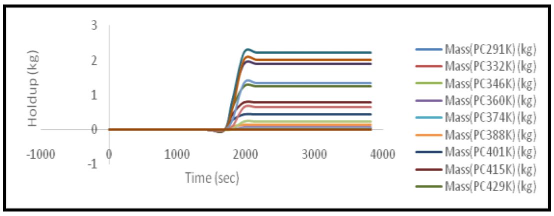

Figure 9: Distillate Receiver 4; Naphtha-Kerosene Slop Mass Hold

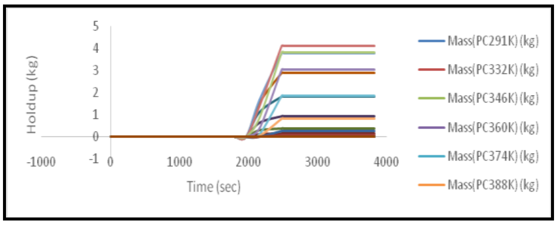

Figure 10: Distillate Receiver 5; Kerosene Mass Hold Up

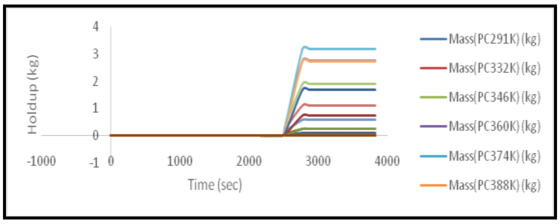

Figure 11: Distillate Receiver 6; Kerosene-Diesel Slop Mass Hold Up

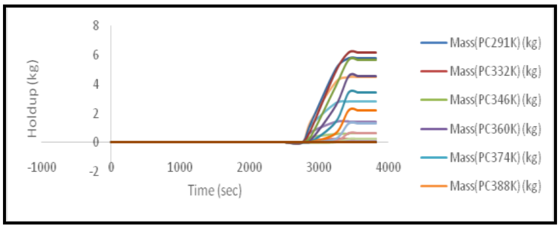

Figure 12: Distillate Receiver 7; Diesel Mass Hold Up

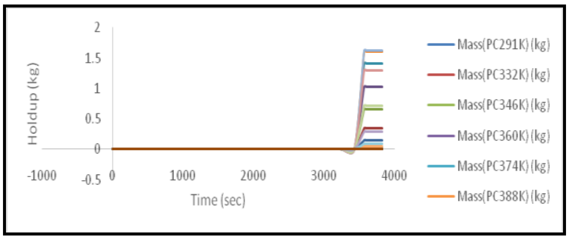

Figure 3.13: Distillate Receiver 8; Diesel-AGO Mass Hold Up

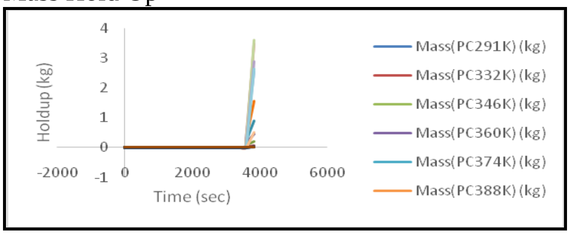

Figure 3.14: Distillate Receiver 9; AGO Mass Hold Up

IV. CONCLUSION

Batch distillation of three Nigerian crude oils (Bonny Light, Forcados and Brass River) was simulated using Aspen Plus simulation software to investigate the effect of crude oil assay on the quantities of distillate cuts obtained. Five fractions (off-gas, naphtha, kerosene, diesel, and AGO) were obtained from the simulation. Bonny Light produced the highest total yield of 61.22% compared to 54.38% and 55.45% for Forcados and Brass River respectively. Generally, the lighter crudes produced higher yields of the lighter cuts while the heaviest crude produced more of the heavier cuts and residue. In particular, Bonny Light favoured the production of off gas, Brass River favoured the production of naphtha and kerosene, while Forcados (the heaviest crude) favoured the production of diesel and AGO.

The study shows that batch distillation can be used in a mini refining plant for the production of petroleum products. Also, the results affirm that crude oil assay affects the distribution of products obtained in a batch distillation unit suitable for a mini modular refinery. Thus, the assay of the crude(s) in the locality a mini modular refinery is to be built should be taken into consideration in the design of batch distillation units. Furthermore, since crude assay could change across an oil field or even in the same well as production progresses, it would be necessary to update the crude assay data regularly to know when to modify the distillation column specifications to enhance the production of the more valuable products. The information obtained from the study can be used to develop detailed feasibility study or investment analysis of mini modular refineries adopting batch distillation units.

The design and investment analysis of a modular mini crude distillation plant using the batch mode will be the subject of another paper. Further studies would be required to investigate the maximum capacity of the plant that can be run efficiently and profitably using batch distillation.

REFERENCES

[1].H. Z. Kister, *Distillation design* (NY: McGraw-Hill, 1992).
[2].Intertek, Crude oil assay. Available through: https://www.intertek.com/petroleum/crude-oil-assay/, 2019, [Accessed 9 April 2020].
[3].K.-j Kim and U. Diwekar, Batch distillation, in E. Korovessi, and A. A. Lininger, *Batch processes*, (New York: CRC Press, 2005) 107-150.
[4].I. Mujtaba, *Batch distillation design and operation* (London: Imperial College Press, 2004).
[5].S. Skogestad, B. Wittgens, R. Litto and E. Sorensen, Multivessel batch distillation, *AIChE Journal*, *43*, 1997, 971-978.
[6].R.V. Kaama, I. Rodríguez-Donisa and V. Gerbaud, V. (2008), Heterogeneous extractive batch distillation of chloroform

methanol water: feasibility and experiments, *Chemical Engineering Science*, 2008, 78-94.

[7]. K.H. Low and E. Sorensen, Simultaneous optimal configuration, design, and operation of batch distillation, *AIChE Journal, 51(6),* 2005, 1700-1713.

[8]. L.T. Biegler, I.E. Grossmann and A.W. Westerberg, *Systematic methods of chemical process design,* (NJ: Prentice-Hall, 1997).

[9]. R.T.B. How, *Simulation of Batch Distillation Column*, final year project, Universiti Tunku Abdul Rahman, Malaysia, 2011.

[10]. R. Maulidda, P.H. Rusmin, A.S. Rohman, E.M.I. Hidayat and D. Mahayana, Modeling and simulation of mini batch distillation column, *Proc. 5th International Conference on Instrumentation, Communications, Information Technology, and Biomedical Engineering (ICICI-BME)*, Bandung, 2017, 1-6.

[11]. M.E.T. Alvarez, E.B. Moraes, J.C. Rodrigues, A.J. Bonon, and M.R. Wolf-Maciel, Evaluation of the batch distillation process in ethanol production, *Proc. 22nd European Symposium on Computer-Aided Process Engineering,* London, 2012: 632-636.

[12]. M. Jibril, A.D. Folorunsho and A. Manasseh, Simulation of Kaduna Refining and Petrochemical Company (KRPC) crude distillation unit using Hysys, *International Journal of Advanced Scientific Research and Technology, 1(2),* 2012, 1-6.

[13]. M. Abusin, A. Basheer, M. Hamed and M. Abdlaziz, Study the effect of variation of crude assay on the design of distillation column, *Journal of Petroleum Engineering and Technology, 6(3),* 2016, 61-76.

[14]. K. Anitha, T. Shuwana and V.R. Kumar, Simulation of atmospheric and vacuum crude units using Aspen Plus, *Petroleum Science and Technology, 29(18),* 2011, 1885-1894.

[15]. J. Haydary and T. Pavlik, Steady-state and dynamic simulation of crude oil distillation using Aspen Plus and Aspen Dynamics, *Petroleum and Coal, 51(2),* 2009, 100-109.

[16]. A.M. Doust, F. Shahraki and J. Sadeghi, Simulation, control and sensitivity analysis of crude oil distillation unit, *Journal of Petroleum and Gas Engineering, 3(6),* 2012, 99-113.

[17]. G.O. John, *Design and cost estimation of a batch fractionating column for crude oil processing,* final year project, Niger Delta University, Wilberforce Island, Nigeria, 2019.