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Modelling and Simulation of a Crude Distillation Unit

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***Abstract*—This paper outlines the technical evaluation, modeling and simulation of a refinery's crude distillation unit (CDU) with the objectives: to provide the most recent flowsheet model on ASPEN HYSYS, carryout different analysis of the CDU to evaluate performance, determine yields of main products and intermediates, ultimate provide adequate data for management's operational decisions. The study first developed the model and verified compatibility with actual design and thereafter used the verified model to carry out a more advanced simulation for objectives listed above. The ASPEN HYSYS model for the design flow and process conditions matched well with the new refineries data based on the Bonny Light crude oil. Overall the converged process conditions showed satisfactory agreement, but some differences which can be attributed to the change in Bonny Light crude oil quality between the time the plant was design and the current crude assay data for the same crude now used for this study. The average product deviation value for volumetric flow rate and temperatures were -17% and 31% respectively while the overall deviation was -48% and 2% for volumetric flow rate and temperature respectively. Three different crudes which includes Bonny Light, Qua Iboe and Forcados were characterized and used to simulate the model by varying the volumetric flow rates from the design value of 993.7m3/hr to a minimum value for the various crudes at which point convergence could not be achieved. It has been revealed from these studies that for targeted product yield like Naphtha, the Bonny Light is best while for good kerosene production, Qua Iboe should be best and Forcados is best for high percentage diesel yield.**

Keywords—crude oil; distillation; hysys; modeling; simulation.

I. INTRODUCTION

In a world where the quest of energy is so enormous, the need for it cannot be over emphasized. Energy is basically the driver of the world's economy, in short everything we do revolves round energy. There are several sources of energy with some of the latest been termed as "renewables" because of their sustainability and some worth eco-friendly, although the "non-renewables" cannot be totally done away with, because Crude oil for example still have a very major role to play in the world of energy. The use of crude oil is so important that all human aspects of life depend on it.

There is therefore the need to tackle the challenges that arise from the rate of energy demand. Non-renewable fuels derived from crude oil, like gasoline (PMS), Kerosene or Diesel are always in high demand especially Premium Motor Spirit (PMS). The Crude Distillation Unit (CDU) which is the most important processing unit in a refinery produces a wide range of product including PMS. There is the need to know the dynamics and best operating conditions of the CDU as well as the feed composition/characteristics. Changes in flow rate and feed composition affects the product yield and product composition, hence the need to model, simulate and study the best amongst many options on how to deliver the best product yield from several crude oil blends [1], [2], [3].

Crude oil is a mixture of thousands chemical compounds, sometimes it can be up to hundreds of thousands of different chemical compounds. Some of these compounds are as simple as CH_4 (methane); others are as complex as $C_{35}H_{50}$ (1-(4-butylcyclohexen-1-yl)-4-[4-(4-heptylcyclohexyl)phenyl] benzene). The chemical formula of CH_4 and $C_{35}H_{50}$ are the shorthand form, Chemist's use to identify individual types of chemical compounds. These compounds mainly have combinations of hydrogen and carbon atoms; hence they are generally called hydrocarbons. Each type of these compounds has its own particular boiling temperature, and therein lies the most useful and used physical phenomenon (fractional distillation) in the petroleum industry [4]. In most cases, crude oil comes from far depths beneath the earth's crust, where the vestiges of animals and plants from millions of years ago have been pressurized and heated over a very long time. It is usually dark brown or black in colour but some can be found as clear liquids and has a characteristic odour that comes from the presence of small amounts of chemical compounds containing nitrogen, sulfur, and metals [5].

In a bid to specify crude oil characteristics, refiners decided to categorize certain compounds into identifiable groups which are called fractions or cuts. These fractions or cuts are derived names for all the compounds that boil between a range of two different temperatures and this is called Cut Points. There are commonly used cut points to describe the various fractions [3], [4].

The CDU is a unit which comprises of a number of separate equipment with various unit operations but the most important amongst them is the main distillation column. The most important aspect of the model is the design and simulation of the atmospheric distillation column and the vacuum distillation column. It is energy intensive and also determines the quality of the product; hence it can have a significant effect on the economics of the unit. In addition to that, by improving the design or operation of the distillation columns, it can maximize the profitability of the refinery [6], [7].

The Crude Distillation Unit comprises of the feed de-salter, heat exchanger network, furnace, atmospheric distillation column and side strippers. All these processes put together allows for the separation of the crude into its various products. There are essentially five products that are obtained from the Crude Distillation Unit, and these include gas plus naphtha, kerosene, light gas oil, heavy gas oil and atmospheric residue [8].

There are three types of crude tower configurations as recognized by [2]:

- U-Towers or RO-Towers (Un-refluxed towers or overhead reflux only towers).
- A-Towers or PA-Towers (Absorption heat removal towers or pumparound towers).
- R-Towers or PD-Towers (Reflux heat removal towers or pumpdown towers).

There are a number of products obtained from the distillation of crude oil. The product yield and amount may vary due to the type of crude processed or the CDU configuration/design. Some of the most important CDU products are [9], [10]:

- **Fuel gas:** This gas consists mainly of lightest fractions; methane and ethane. Some refineries produce propane in excess of liquefied petroleum product (LPG) requirements which is also included in the fuel gas stream. Sometimes this stream is usually called the dry gas.
- **Wet gas:** The wet gas stream is made up of propane and butanes which also includes methane and ethane. The propane and butanes are separated to be used for LPG while some of the butanes are used for gasoline blending and feed for the alkylation unit.
- **Light Straight Run Naphtha.** The stabilized LSR naphtha also known as LSR gasoline stream, when desulfurized, can be used in gasoline blending or it is further processed in an isomerization unit to improve the octane number before been blended with gasoline.
- **Heavy Straight Run Naphtha:** This can also be referred to as the HRS gasoline. In most cases naphtha are mainly used as feed for catalytic reformer to produce high octane reformate which is then used for gasoline blending and aromatics.
- **Gas oils:** There are a number of gas oils, which includes; the light, atmospheric, and vacuum gas oils. They are all processed in the catalytic cracker or hydrocracker units to produce gasoline, jet fuels and diesel fuels. The vacuum gas oils which are heavier can be used also as lubricating oil process units feedstock.
- **Residuum:** This is the heaviest fraction which includes the vacuum still bottoms and can be processed in a coker unit, visbreaker unit or a deasphalting unit to produce heavy fuel oil and lube base stocks. In the case of asphalt crudes, the residuum can be further processed to produce asphalts used for roofing or road.

The design and simulation of the distillation columns involves categorizing the crude oil into different pseudo-components. Then chose a thermodynamic model for the vapour-liquid equilibrium and do calculations for the thermodynamic properties. The cubic equations of state is a good model while the Peng–Robinson equation is the recommended physical property data for hydrocarbon mixtures; it has been proven to have best success factors and also it is the most frequently used models for many petroleum mixtures and hydrocarbon. The next step is to enter the simulation environment: select appropriate unit operations, streams (including energy/utility streams) and to do the unit operations tray to tray or stage-wise distillation calculations. With respect to certain specification for the products, do an energy balance, mass balance and a vapour liquid equilibrium relations calculation for each of the tray. Aspen Hysys simulation software can be used for comprehensive simulation of the CDU units. Results are generated and analysis can be done as well [11], [12] – [20].

A technical survey was done in the refinery company under investigation, wherein; data sheets for the survey were obtained and used for this study. Data (including crude assays), flowsheet and process conditions obtained from the survey were deployed into the modeling and simulation of the CDU [21].

II. Methodology

A. *Modelling Environment*

The CDU was modeled and simulated using the Aspen Hysys V8.6. The plant model was set up in Aspen Hysys using the Peng-Robinson fluid package.

The feed type is raw crude of Bonny light with the following crude assay (Table 1):

TABLE 1. BONNY LIGHT CRUDE ASSAY [21]

WHOLE CRUDE	
Gravity, °API	32.9
Specific Gravity	0.86
Sulfur, wt. %	0.16
Nitrogen, ppm	1170
Pour Point °F	6.1
Pour Point °C	-14.4
Acid Number, mg KOH/g	0.19
Back-Blended Acid, mg KOH/g	0.17
Viscosity @ 40 °C (104 °F), cSt	4.99
Viscosity @ 50 °C (122 °F), cSt	4.05
Asphaltenes, C7, %	0.0032
Nickel, ppm	4.16
Vanadium, ppm	0.42
Characterization Factor, K	11.68

Based on the above whole crude and the TBP data the crude assay was successfully characterized, developed and installed to be used for the modeling and simulation.

Hysys Flowsheeting And Simulation Model The crude entering the flash drum (CrudeBlend) was at a temperature of 226°C and a feed rate of 972.4m3/hr. The lighter vapour fraction was taken out from the top of the drum while the heavier fraction went out via the bottom of the drum, it then enters the furnace and leaves at a temperature of 360.3°C, this is then combined with the overhead vapour in the feed mixer where temperature is reduced to about 336°C at a rate of 972.8m3/hr. This is the column charge which enters the main fractionator at the flash zone. The hot crude flashes and the lighter vapour fractions move up the column while the heavier fractions moves down to the bottom of the column. Three pumparounds (PA1, PA2, and PA3) are used to take out heat from the fractionating column while three sidestrippers (Kero_SS, Diesel_SS and AGO_SS) were used to further distill the various products. A Kero_SS Reboiler was used and a Condenser for separating the lighter gases from the Naphtha at the top of the fractionating column.

C. Parameters of Unit Operations:

The pressure drop across the heater was inputted at 1kPa, while the temperature drop across the heater was calculated by the crude column mixer.

The mixer temperature was set at **336°C**, and the outlet pressure was set to lowest inlet.

The main distillation column has 48 trays with three feed streams: Crude charge, main column steam (stripping steam) and an energy stream (Q-trim); and was modeled with three pumparounds. Below are some of the crude column specifications (Table 2) together with data for the kerosene, diesel and AGO side strippers (Tables 3 - 5).

TABLE 2. CRUDE COLUMN SPECIFICATION

Crude Column	Value
Trays	48
Crude Charge	47__Main TS
Energy Stream (Q-Trim)	47__Main TS
PA_1_Return	1__Main TS
Diesel_SS_Return	23__Main TS
AGO_SS_Return	33__Main TS
PA_2_Return	13__Main TS
VBP_1_ByPassStrm	43__Main TS
PA_3_Return	22__Main TS
Kero_SS_Return	10__Main TS
Top operating pressure	87.28kPa
Bottom Operating Pressure	107.87kPa
Internal Type	Sieve
Weir Height [mm]	50
Weir Length [m]	1.2
DC Volume [m3]	8.84E-02
Active Area [m2]	1.263938747
Flow Paths	1
Weeping Factor	1
PA_1_Rate(Pa)	673000
PA_1_Duty(Pa)	1000000
PA_2_Rate(Pa)	673000
PA_2_Duty(Pa)	10000000
PA_3_Rate(Pa)	325000
PA_3_Duty(Pa)	10000000
Reflux Ratio	6
VBP_1_Rate(Pa)	27180
Diesel_SS_Return Temp	225
AGO_SS_Return Temp	267
Flashzone Temp	320
Vapour Flow	83

TABLE II. KERO SIDE STRIPPER SPECIFICATION

Specifications	**Value**
Kero_SS BoilUp Ratio	0.75
Kero_SS_Return Temp	183
Stages	6

TABLE 3. DIESEL SIDE STRIPPERS SPECIFICATION

Specifications	**Value**
Diesel_SS Prod Flow	201000
Diesel_SS_ReturnTemp	225
Stages	4

TABLE 4. AGO SIDE STRIPPER SPECIFICATION

Specifications	Value
AGO_SS Prod Flow	39230
AGO_SS_ReturnTemp	267
Stages	4

D. Other Crude Assay

As part of the analysis of the model other crude oils were studied as follows (Tables 6 – 8):

TABLE 5. QUA IBOE CRUDE ASSAY

QUA IBOE	
Property	**Bulk Value**
SulfurByWt (%)	0.118179261
StdLiquidDensity (kg/m3)	831.0649051
KinematicViscosity (cSt)@ 37.78 (C)	3.551259656
Watson K	11.67262908
PourPoint (C)	-4.017613515
TotalAcidNumber (mg KOH/g)	0.153
CutYieldByVol (%)	100
KinematicViscosity (cSt)@ 15 (C)	4.399837638
KinematicViscosity (cSt)@ 40 (C)	3.46847156
ConradsonCarbonByWt (%)	0.930885833
VanadiumByWt (%)	3.20E-05
NickelByWt (%)	0.000350686
ParaffinsByVol (%)	19.98471608
NaphthenesByVol (%)	60.85932965
AromByVol (%)	19.15595427
RONClear	49.38713511
AnilinePoint (C)	64.14573946
SmokePt (m)	0.010476127
FreezePoint (C)	6.550456683
NitrogenByWt (%)	0.050665157
RVP (kPa)	13.11735482

TABLE 6. FORCADOS CRUDE ASSAY

FORCADOS	
Property	**Bulk Value**
SulfurByWt (%)	0.285908121
StdLiquidDensity (kg/m3)	867.4740387
KinematicViscosity (cSt)@ 37.78 (C)	7.539852721
Watson K	11.41511368
PourPoint (C)	-20.59278455
TotalAcidNumber (mg KOH/g)	0.153
CutYieldByWt (%)	100
KinematicViscosity (cSt)@ 10 (C)	10.02391236
KinematicViscosity (cSt)@ 100 (C)	1.97620295
NaphthenesByVol (%)	31.74974785
AromByVol (%)	28.28664291

III. RESULTS AND DISCUSSION

Aspen Hysys have been used to develop the CDU model and the design data from the Crude Distillation Unit in the refining company under study (Figs. 1 and 2) has been used to validate the model. Thus, the following results were obtained from running the model.

Table 8 shows the percentage deviation of the hysys result from the design data. The average product deviation from design data was -17% for product yield and 31% for the temperature. The overall average deviation from design data was -48% for the entire flow rate while the temperature was 2%. The crude used was the Bonny light.

Table 9 (Change in volumetric flow rate to percentage product yield for Bonny Light Crude) shows that decrease in volumetric flow rate of the crude causes change in the percentage yield of the various products as shown in the table. The minimum flow rate for which the column could not converge was at 600m3/hr.

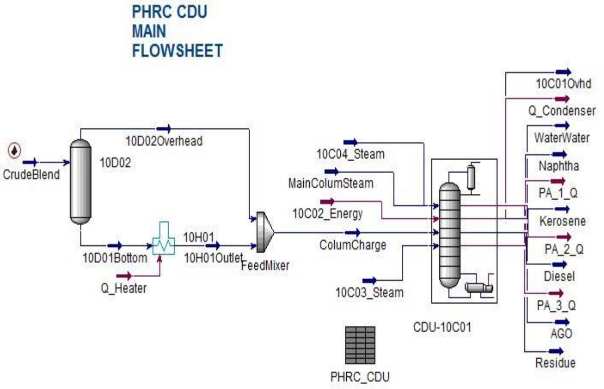

Fig. 1. *CDU of the Refinery Main Flowsheet.*

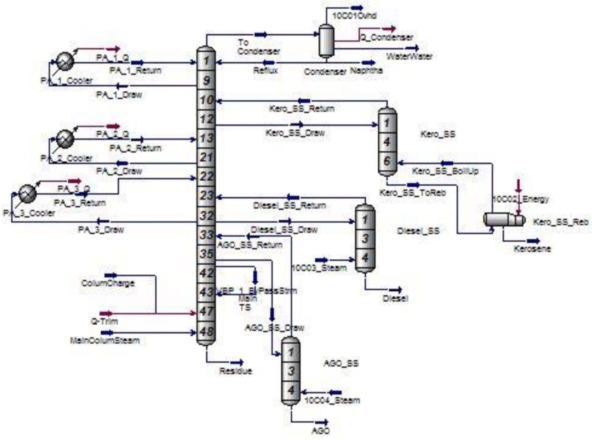

Fig. 2. *Main fractionator.*

The plot of percentage Naphtha yield versus flow rate for Bonny Light Crude (Fig. 3) shows that decreasing the volumetric flow rate leads to a decrease in the percentage Naphtha yield. It can be seen from the plot of percentage Kerosene yield versus flow rate for Bonny light crude (Fig. 4) that a decrease in the volumetric flow rate initially caused an increase in percentage kerosene yield until it got to a maximum yield of 28.95% at a flow rate of 775m3/hr after which the yield began to decline.

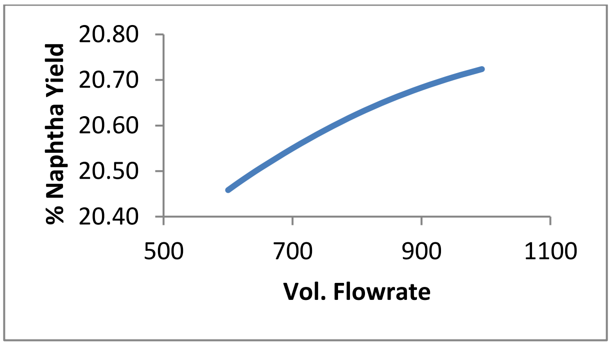

Fig. 3. *Percentage Naphtha yield versus flow rate for Bonny Light Crude*

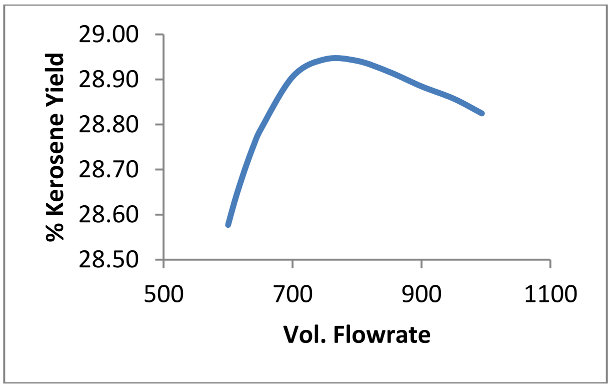

Fig. 4. *Percentage Kerosene yield versus flow rate for Bonny Light Crude*

Fig. 5. *Percentage Diesel yield versus flow rate for Bonny Light Crude*

In Fig. 5 (Percentage Diesel yield versus flow rate for Bonny Light Crude) it can be seen that that a decrease in flow rate causes an increase in diesel yield.

For Qua Iboe Crude (Fig. 6), the decrease in volumetric flow rate causes an increase in percentage yield of Naphtha, with the minimum flow rate for which the column could not converge been 300m3/hr and the percentage naphtha got a maximum yield of 20.58%.

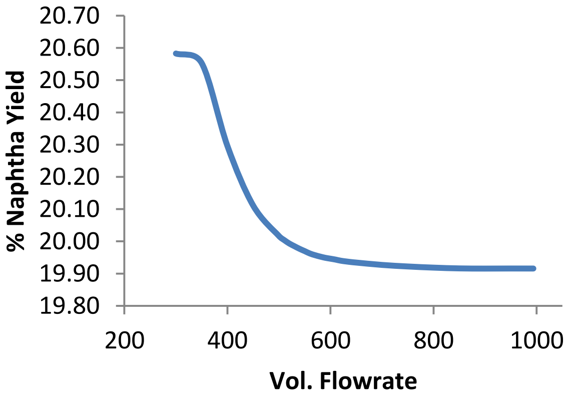

TABLE 8. MODEL DEVIATION FROM DESIGN

Fig. 2. *Percentage Naphtha Yield versus Volumetric Flowrate for Qua Iboe Crude*

A plot of the percentage Kerosene yield versus volumetric flow rate for Qua Iboe Crude (Fig. 7) has shown that kerosene yield reduces with decreasing volumetric flow rate, while in Fig. 8 (Percentage Diesel yield versus flow rate for Qua Iboe Crude) the decrease in flow rate produces increase in percentage diesel yield.

Similar studies on the change in volumetric flow rate to percentage product yield for Forcados Crude have shown that decrease in volumetric flow rate causes changes in percentage product yield of Forcados crude. At 14.89% of Naphtha yield, the minimum flow rate for which the column could not converge was at 420m3/hr. Evident from Fig. 9 is the fact that a decrease in volumetric flow rate causes increase in percentage Naphtha yield, while Fig. 10 (Percentage Kerosene yield versus volumetric flow rate for Forcados Crude) shows the reverse, that is, decrease in flow rate causes decrease in percentage kerosene yield.

In Fig. 11 (Percentage Diesel yield versus volumetric flow rate for Forcados Crude) shows an inverse relationship, where the decrease in volumetric flow rate causes an increase in the percentage yield of diesel.

Table 10 shows the flow rates of various products of the different crudes. Bonny light had the highest naphtha rate of 205.93m3/hr, followed by Qua Iboe and Forcados at 197.9m3/hr and 136.01m3/hr respectively. Qua Iboe had the highest kerosene rate of 312.47m3/hr while Bonny light had 286.39m3/hr and Forcados had 140.44m3/hr. The highest Diesel rate, AGO rate and AR rate was from Forcados with values of 129 m3/hr, 120.48 m3/hr and 461.04m3/hr respectively. The second highest rate of Diesel (22.52 m3/hr) and AGO (101.23 m3/hr) was from Qua Iboe but it had the least rate of AR of 352.32 m3/hr. Bonny light had the least Diesel and AGO rate of 16.23 m3/hr and 67.98 m3/hr respectively while it also gave second to the highest AR rate of 409.76 m3/hr.

	DESIGN	HYSYS	DESIGN	HYSYS	% Flowrate Deviation	% Temp Deviation
Crude Oil/Main	Vol Flowrate(m3/hr)	Vol Flowrate(m3/hr)	Temp (deg. Cel.)	Temp (deg Cel.)		
CrudeCharge	993.70	993.70	202.00	202.00	0%	0%
10D02Ovhd	20,150.00	46466.95	202.00	202.00	-131%	0%
10D02Bttoms	894.90	710.45	202.00	202.00	21%	0%
10HO1Outlet	894.90	710.45	353.00	373.25	21%	-6%
Total (Ovd+Bott)		47177.39				
Designcruderate						
Turndownratio[%]						
Main CDU Column						
Feed	993.70	993.70	336.00	336.00	0%	0%
PA_1_Draw	720.60	820.19	147.00	144.71	-14%	2%
PA_1_Return	720.60	820.19	60.00	145.20	-14%	-142%
PA_2_Draw	807.90	769.50	221.00	247.54	5%	-12%
PA_2_Return	807.90	769.50	155.00	252.46	5%	-63%
PA_3_Draw	507.00	369.19	276.00	265.08	27%	4%
PA_3_Return	507.00	369.19	235.00	273.75	27%	-16%
Kero_SS_Draw	168.10	440.39	195.00	176.84	-162%	9%
Kero_SS_Return		154.01	208.00	183.00		12%
Diesel_SS_Draw	295.90	38.22	276.00	265.08	87%	4%
Diesel_SS_Return		27.60	267.00	225.00		16%
AGO_SS_Draw	52.40	88.57	322.00	274.07	-69%	15%
AGO_SS_Return		21.63	316.00	267.00		16%
Kero_SS_Boilup		192.40		205.45		
Kero_SS_ToReb	96.50	478.80	233.00	194.50	-396%	17%
To Condenser	69,510.00	295898.79	132.00	114.65	-326%	13%
Products						
10C01Overhead		7.76	132.00	52.60		60%
Naphtha	300.10	205.93	132.00	52.60	31%	60%
Kerosene	140.10	286.39	233.00	205.45	-104%	12%
Diesel	233.50	16.23	257.00	173.85	93%	32%
AGO	43.70	67.98	308.00	248.43	-56%	19%
AR	276.30	409.76	326.00	309.50	-48%	5%
Water		12.98		52.60		
				Ave. Product Deviation	-17%	31%
				Overall Ave. Deviation	-48%	2%

Table 9. Change in Volumetric flow rate to percentage product yield for Bonny Light Crude

BONNY LIGHT, NIGERIA						
Vol. Flowrate	10C01Overhead	Naphtha	Kerosene	Diesel	AGO	AR
993.7	0.78	20.72	28.82	1.63	6.84	41.24
950	0.82	20.71	28.86	1.71	6.91	41.03
900	0.86	20.68	28.88	1.83	7.02	40.77
850	0.91	20.66	28.92	1.95	7.13	40.48
800	0.96	20.63	28.94	2.10	7.26	40.16
750	1.02	20.59	28.94	2.27	7.42	39.80
700	1.09	20.55	28.91	2.50	7.62	39.39
650	1.17	20.51	28.79	2.80	7.87	38.92
640	1.19	20.50	28.75	2.87	7.93	38.81
630	1.21	20.49	28.72	2.94	7.99	38.71
620	1.23	20.48	28.67	3.02	8.05	38.60
610	1.25	20.47	28.63	3.11	8.12	38.49
600	1.27	20.46	28.58	3.20	8.18	38.37

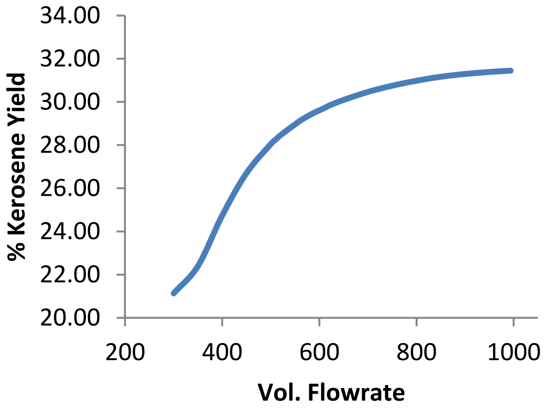

Fig. 3. *Percentage Kerosene yield versus flow rate for Qua Iboe Crude*

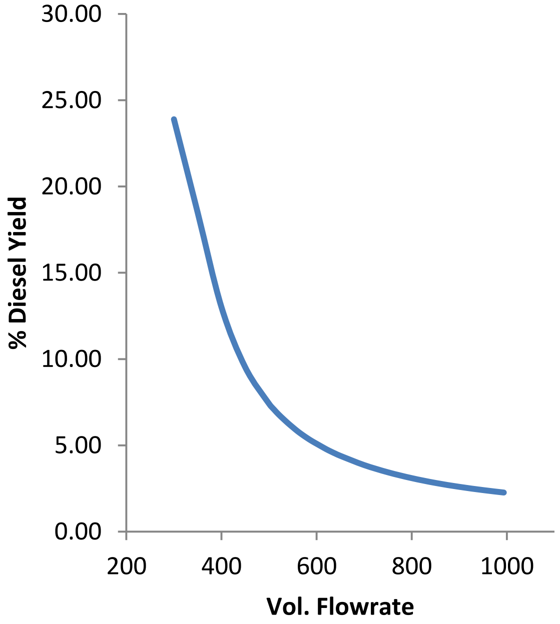

Fig. 4. *Percentage Diesel yield versus flow rate for Qua Iboe Crude*

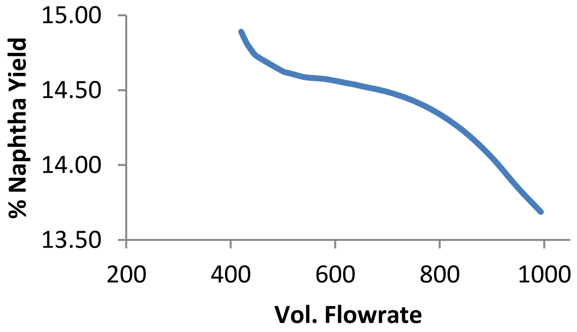

Fig. 5. *Percentage Naphtha Yield versus Volumetric Flowrate for Forcados Crude.*

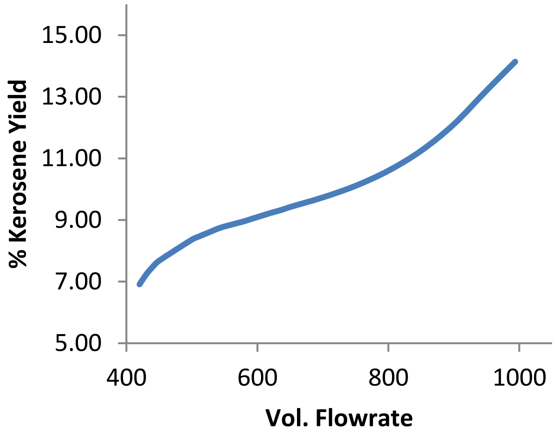

Fig. 6. *Percentage Kerosene yield versus Volumetric Flowrate for Forcados Crude.*

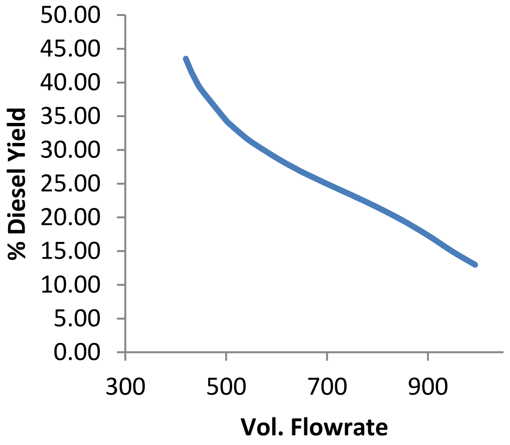

Fig. 7. *Percentage Diesel yield versus Volumetric Flowrate for Forcados Crude.*

TABLE 10. PRODUCT FLOWRATES OF DIFFERENT CRUDES AT 993.7M3/HR.

	Bonny Light	Qua Iboe	Forcados
10C01Overhead	7.76	7.65	7.01
Naphtha	205.93	197.90	136.01
Kerosene	286.39	312.47	140.44
Diesel	16.23	22.52	129.00
AGO	67.98	101.23	120.48
AR	409.76	352.32	461.04

IV. CONCLUSIONS

From the results obtained, the studies have shown that the hysys model has a volumetric flow rate and temperature deviations that is somewhat fair. Three different crudes (Bonny light, Qua Iboe and Forcados) were used and the volumetric flow rates were gradually decreased from the design value of 993.7m^3/hr to the minimum flow rate values of the different crudes.

The model showed the three best product yields of the three different crudes. Bonny light had the best percentage Naphtha yield of 20.46% at a minimum volumetric flow rate of 600m^3/hr. The best percentage Kerosene yield was from Qua Iboe crude with a value of 31.45% at a maximum volumetric flow rate of 993.7m^3/hr. Forcados Crude gave the best percentage Diesel yield of 43.53% at minimum volumetric flow rate of 420m^3/hr.

It can be deduced that Qua Iboe is a good close substitute to Bonny light when the yield of naphtha is considered as the target product, in situations where Bonny light is unavailable. The best alternative to higher kerosene yield is Bonny light crude because it has a maximum percentage kerosene yield of 28.95% at a flow rate of 775m^3/hr. Hence, during the processing of Bonny light crude, if more kerosene is desired then at 775m3/hr volumetric flow rate, kerosene yield will be highest.

It can thus be inferred that Bonny Light crude contains more of Naphtha, while Qua Iboe crude is more kerosene base and Forcados seem to be the heaviest as it is contains more diesel.

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