

**Full Length Research**

**MODULAR CRUDE OIL TOPPING REFINERY: THE TOTAL UTILIZATION OF ALL DISTILLED CUTS**

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**ABSTRACT**

Received 16 November, 2016  
Revised on the 27 November, 2016  
Accepted 2 December, 2016

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The most feasible solution to the low refining output from the Nigeria government owned refineries still remains the establishment of modular refineries at strategic locations within the country. The different forms of modular refineries ranging from the atmospheric unit to the full conversion unit have successfully been applied in different areas of the world, albeit the establishment of modular topping refinery seems to be ideal since the country is relatively new to the idea. The limitation of this concept remains the channeling of both the atmospheric residue and naphtha since Nigeria does not currently have a ready-made market for them. Conventionally the atmospheric residue cannot be further heated in an atmospheric condition to produce more supposed vacuum products due to: over straining on the furnace to provide the necessary heat needed, fouling on both the distillation column and heating medium, and a future decline of efficiency from the heater. A vacuum distillation column is therefore used to distil at a lower pressure at the expense of an additional cost of units. This study attempts to proffer a solution by designing a 10,000 barrel per day single integrated atmospheric distillation column that can refine crude oil feed and concurrently produce both standard atmospheric products and "supposed" vacuum products (all distilled cuts) under atmospheric condition. Through the introduction of a submerged combustion zone into the stripping section of a conventional distillation column where Naphtha is totally utilized as the source of fuel, 369.97 ft<sup>3</sup>/hr, 3.890 ft<sup>3</sup>/hr, 1.507 ft<sup>3</sup>/hr, 730.13 ft<sup>3</sup>/hr, 812.49 ft<sup>3</sup>/hr, 170.16 ft<sup>3</sup>/hr, 590.65 ft<sup>3</sup>/hr, 190.97 ft<sup>3</sup>/hr, 150.07 ft<sup>3</sup>/hr, 0.000000539 ft<sup>3</sup>/hr, 0.0000150 ft<sup>3</sup>/hr, 0.0000152 ft<sup>3</sup>/hr and 377.14 ft<sup>3</sup>/hr of Off Gas, Light Naphtha, Heavy Naphtha, Kerosene Diesel, AGO, Fuel Oil, Lube Oil, LTGO, HTGO, Paraffin, Residue and Asphalt, respectively were successfully brought out.

**Keywords:** Modular, Topping, Refinery, Atmospheric, Nigeria, Submerged, Crude Oil

**INTRODUCTION**

Crude oil as discovered in the oil field is a complex mixture of hydrocarbon compounds (Paraffins/Naphthenes/Aromatics), non-hydrocarbon compounds (sulphur/nitrogen/oxygen), water and

gases with different quantities of metallic compounds. In its unprocessed form, crude oil is generally not suitable for any industrial application, petroleum refineries are therefore required to convert or refine its unprocessed form into more useful products using both physical separation and chemical conversion processes (Matar and Hatch, 2001). The physical separation processes generally separate the crude oil mixture without altering the chemical characteristics of its components (Matar and Hatch, 2001). The chemical conversion processes which are either thermal or catalytic help to upgrade lower value fractions into products better adapted to the markets (Leprince, 2001).

Although the importance of an operational crude refinery in any country cannot be underestimated as its products find applications in everyday life, Nigeria government owned refineries still record low refining output as none can boast of working above 60 percent of its designed capacity (NNPC Annual Bulletin, 2001-2013). This situation has led to large money being spent on the importation of refined products, high rate of unemployment, under-utilization of crude oil feed and a bad reputation among other oil producing countries.

In an attempt to provide solutions to the above unfavorable scenario, the country is left with the following options: establishment of more conventional refineries, legalizing of the illegal refineries, swapping of our crude with refined products from other countries and setting up of modular refineries around the country. The establishment of more conventional refineries seems to be moving at a snail speed, the legalization of the illegal refineries brings mixed feelings among citizens while the swapping of crude oil for refined product serves as a temporary solution as there is currently no direct measure of calculating the exact refined products for raw crude oil. This leaves the country with the most feasible option of setting up modular refineries at strategic locations within the country.

A modular refinery is a conventional refinery constructed in a fragmented way (Brown, *et al*, 2003) or simply a big refinery in miniature form (Igwe, 2015). Globally this concept is applied successfully when crude oil and a ready market are available but low refining capacity is recorded. Although the configuration of a modular refinery comes in different packages, this study will focus on the physical

separation processes which include the Atmospheric and Vacuum Added Distillation units

### The Atmospheric Distillation Unit

Although there are different configurations of an atmospheric distillation unit, its main equipment consists of the distillation column, condenser, heat exchanger networks and furnace while other features remain optional. Figure 1 below shows the widely accepted pattern where the crude oil feed is passed through series of heat exchangers network before entering the de-salter which helps to remove water containing salts.

The desalted crude enters another heat exchanger network before entering the furnace where it is heated to about 340-370 °C to give the required percentage of vaporization (Bagajewicz and Ji, 2001). The feed enters into the distillation column via the flash zone while the overhead condenser and pump-around circuits along the column effectively remove heat within the column. Side stripping or steam also helps in removing light components from liquid products (Bagajewicz and Ji, 2001)

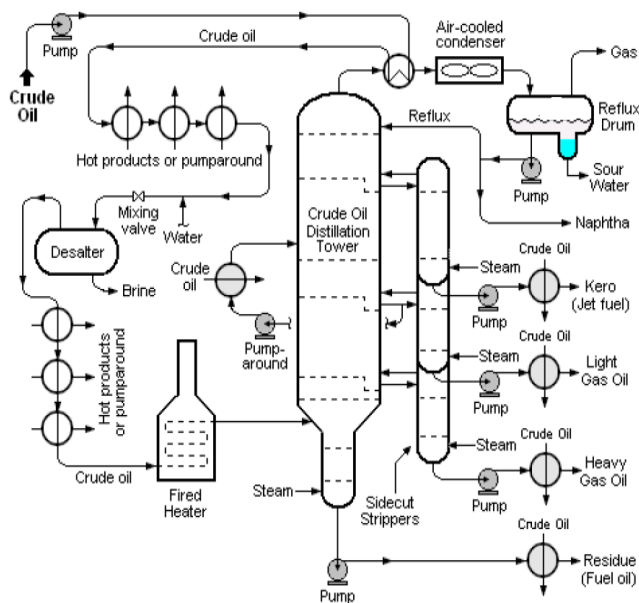


Figure 1: A Modular Crude Oil Topping Refinery  
(Source: Errico *et al*, 2009)

Product such as heavy naphtha, kerosene and gas oil (diesel) are withdrawn as side streams while the residue is removed from the bottom of the distillation tower and are either used as fuel oil or charged to a vacuum distillation unit. From the overhead condenser, uncondensed gases are removed while

condensed light naphtha is sent to the storage (Bagajewicz and Ji, 2001).

### Vacuum Distillation Unit

The vacuum distillation process occurs at a reduced density and absolute pressure of 25–40 mmHg with a temperature range of 340–540°C. Its major objective is to increase the amount of middle distillates, produce lubricating oil base stocks and asphalt. (Matar and Hatch, 2001). The distillation process occurs in three forms namely: dry vacuum, wet vacuum and semi wet. The dry vacuum works without the injection of steam, the wet vacuum ensures that steam is injected both in the furnace feed and at the bottom of the tower while in the semi-wet process, steam is injected only at the bottom of the tower (Wauquier, 2000). The vacuum is produced by ejectors or a combination of ejectors and liquid ring pump (Hsu and Robinson, 2006). Superheated steam is important for the process as it tends to decrease the partial pressure of the hydrocarbons and reduces coke formation in the furnace tubes. Table 1 shows the different distillate cuts both from the atmospheric and vacuum distillation products with their boiling points

Table 1: Destinations for Straight – Run Distillates.

Fraction	Boiling Point(°C)	Next Destination
LPG	-40 to 0	Sweetener
Light Naphtha	39-85	Hydrotreater
Heavy Naphtha	85-200	Catalytic Reformer
Kerosene	170-270	Hydrotreater
Diesel	180-340	Hydrotreater
Vacuum Gas Oil	340-566	Fluid Catalytic Cracker, Hydrotreater, Lube Plant and Hydrocracker
Vacuum Residue	>540	Coker, Visbreaker, Asphalt Unit and Hydrotreater

Source: (Hsu and Robinson, 2006)

Generally most Nigeria crude contains a high percentage of residues after the atmospheric distillation stage. The channeling of the residue is a big challenge as all cannot simply be used as a process fuel either for pre- heating or fuel for the heating system. The final use of both light Naphtha and heavy Naphtha also indicates a great problem since Nigeria does not currently have a ready-made market for them.

Conventionally the atmospheric residue cannot be further heated in an atmospheric condition to produce more supposed vacuum products due to: over straining on the furnace to provide the necessary heat, fouling on both the distillation column/heating medium and a future decline of efficiency from the heater. A vacuum

distillation column is therefore used to distil at a lower pressure at the expense of an additional cost of units. This leaves us with two major questions- Firstly is it possible to have a single atmospheric distillation column that can refine crude oil feed and concurrently produce both standard atmospheric products and “supposed” vacuum products (all distilled cuts) under atmospheric condition concurrently without any interference? Secondly, how best can naphtha be utilized for maximum productivity?

The study aimed to design an atmospheric distillation column with an additional source of heating that can refine 10,000 barrels per day (bpd) of bonny medium crude and produce all distilled cuts all under atmospheric condition.

## MATERIALS AND METHODS

### Materials

Bonny light, Bonny Medium, Qua Iboe, Brass and NDPR were used for crude assays. Equipment used include Aspen Hysys Simulator version 8.6 and Autodesk Inventor.

### Method

Assuming atmospheric conditions on a typical distillation column; characterization of bonny medium crude via Aspen Hysys simulator was carried out to determine the average properties of the various atmospheric distillation products. With a design capacity of 10,000 bpd and a fixed temperature of 358.31°C and pressure of 700 kPa of crude entering the main distillation column, necessary operating conditions were derived. Design of suitable tray for the process with values gotten from the simulation process was done via Autodesk Inventor. Design of all parts of the integrated distillation (disengagement, rectifying, stripping and the submerged combustion zone) was done via Autodesk Inventor, where the disengagement height was calculated via equation (1) and (2) and diameter via equation (3)

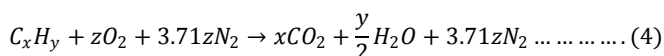
$$q = CA\sqrt{2g_n h_t} \dots \dots \dots (1)$$

$$q = CA\sqrt{\frac{2\Delta P}{\rho}} \dots \dots \dots (2)$$

$$D = \sqrt{\frac{4A}{\pi}} \dots \dots \dots (3)$$

Where  $q$  is flow rate,  $C$  is flow coefficient,  $A$  is cross section area,  $\Delta P$  is pressure drop,  $\rho$  is density,  $g_n$  is acceleration of gravity and  $h_l$  is head loss.

Naphtha was used as the source of fuel for the submerged combustion zone; therefore the operating condition of the combustion process was also determined based on the stoichiometric equation (4) and (5)



$$\text{Where } z = x + \frac{1}{4}y \dots \dots \dots (5)$$

Another simulation was carried out for the overall integrated distillation column to ascertain the credibility of the insertion of the submerged combustion zone. All distilled products were compared against ASTM standard

## RESULTS AND DISCUSSION

### Crude Oil Characterization

Characterization of bonny medium crude was done based on their true boiling point using Aspen Hysys Simulator to determine the maximum liquid volume fraction of the different distillate that can be gotten from the crude at an ideal condition as shown in Table 2.

Table 2: Average Properties of ADU Products

Stream	Vol.%	SG	API	S%
Off Gas	1.2	0.52	47.11	0.05
Light Naphtha.	0.9	0.66	105.6	0.19
Heavy Naphtha.	8.5	0.89	99.07	0.02
Kerosene	11	0.95	45.49	0.06
Diesel	31.7	0.97	32.67	0.13
AGO	10	0.96	8.785	0.2
Atmospheric Residue	36.7	0.99	6.22	0.31
Whole Crude	100	0.86	2.65	0.16

### Determination of Operating Conditions

With a design capacity of 10,000 bpd and a fixed temperature of 358.31°C and pressure of 700 kpa of crude entering the main distillation column, simulation was done to show both the process flow (Figure 2) and operating conditions of the process (Table 3, 4 and 5).

The different product tray positioning and their discharge temperature are shown in Table 5.

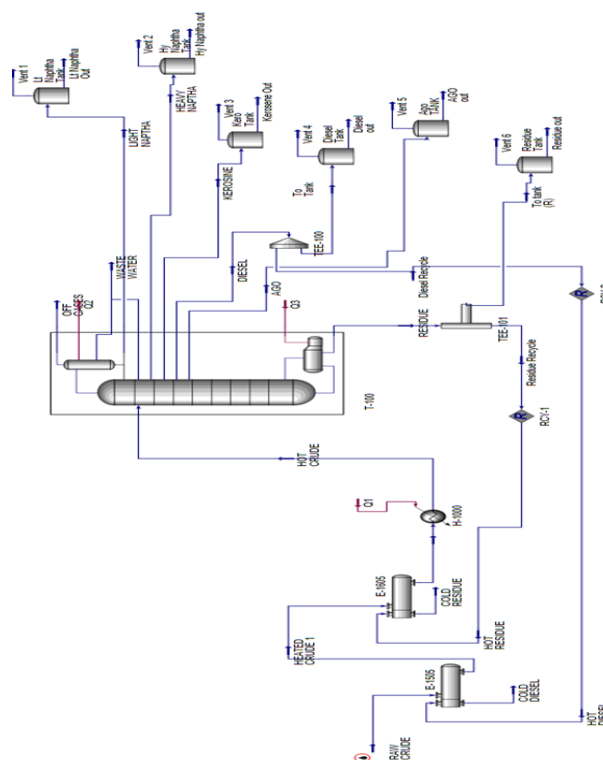




Table 5: Product Discharge Temperature and Tray Location

Tray	Position	Temperature(°C)
Off Gas	1	46.29
Light Naphtha	1	46.29
Heavy Naphtha	2	76.53
Kerosene	16	139.13
Diesel	24	273.13
AGO	30	340.02
Feed Entry	31	358.31

### Selection of Tray

Sieve tray was used due to its high capacity, low to moderate pressure drop, high efficiency, low maintenance, low fouling tendency and low cost when compared to the others. Table 6 shows its internal features with values gotten from the simulation process while Figure 3 and 4 show its orthographic and isometric representation done via inventor software.

Table 6: Tray Internal Features

Properties	Value
Tray Diameter	4.92 ft (1.5 m)
Tray Spacing	1.464 ft (0.5 m)
Tray Volume	31.23 $ft^3$ (0.884 $m^3$ )
Tray Hold up	3.120 $ft^3$ 0.0883 $m^3$ )
Pressure Drop	1.111 kPa
Stage Efficiencies	1
Tray Hole Diameter	5 mm (0.005 m)
Tray Hole Pitch	15 mm (0.015 m)

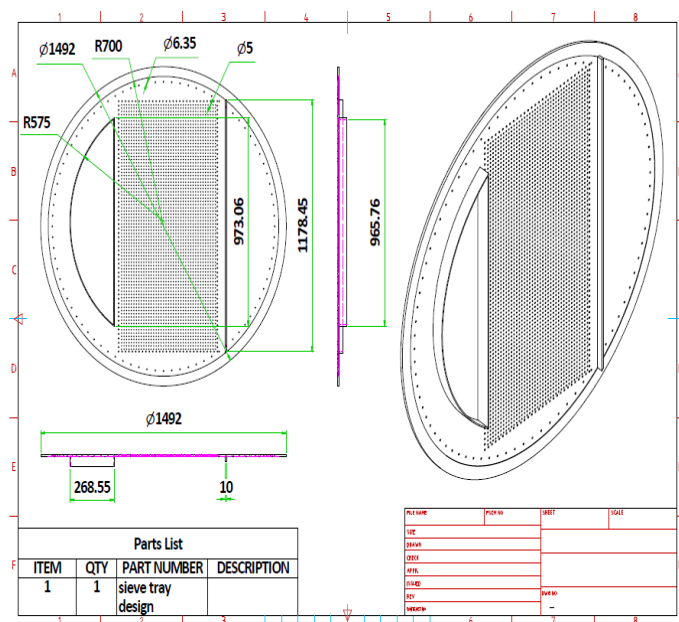


Figure 3: Sieve Tray Orthographic Diagram

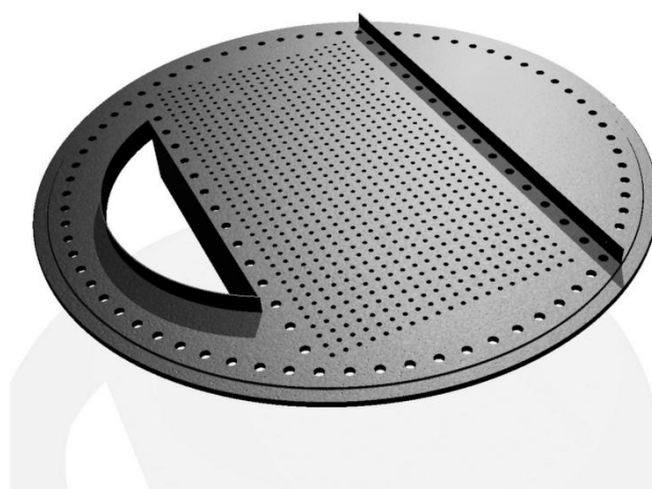


Figure 4: Sieve Tray Isometric Diagram

### Integrated Distillation Column

From previous analysis, the entire length attributing to the atmospheric products aspect of the integrated column was deduced as 21.03 m (69 ft.). The column design was broken down into different sections for easy analysis and description as shown in Figure 5.

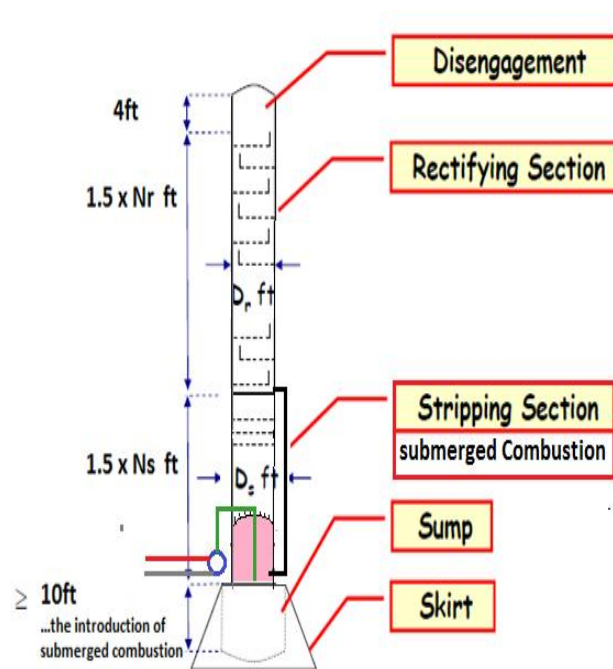


Figure 5: The Different Sections of the Integrated Distillation Column

### Disengagement Section

The disengagement height is the added height to the original height of the calculated column. It is usually

4ft for most columns and aids the disengagement of the top column for maintenance work and the projection of the outlet nozzle for off gas production as well as the reflux chamber.

Given  $\Delta P = 0.1612$  psi (23.21 lb/ft<sup>2</sup>),  $\rho = 0.156$  lb/ft<sup>3</sup>,  $q = 0.1027$  ft<sup>3</sup>/s flow coefficient of 0.96 and  $g_n = 32.174$  ft/s. The flow rate through nozzles was calculated using equation (1) and (2), where the cross sectional area was gotten as 0.002768 ft<sup>2</sup>, which was inserted into equation (3) to get a diameter of 0.5938 ft (7.1256 in). With the aid of the inventor design tool, the disengagement section is designed and shown in Figure 6.

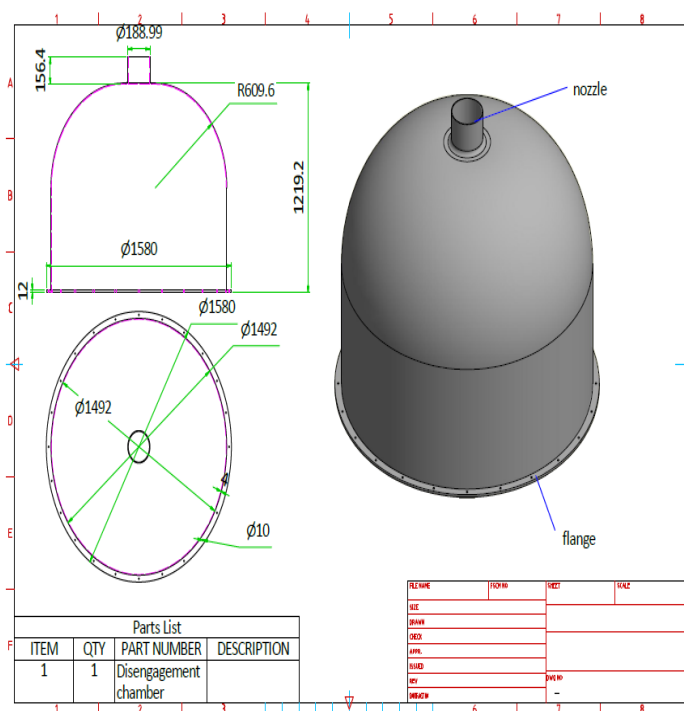


Figure 6: Disengagement Section

## Rectifying Section

This was the largest portion of the entire distillation column, being the section above the feed tray. With a tray spacing of 1.5 ft and a total number of 30 trays, the total length of this section and the corresponding outlet nozzles for the production of the different products of the column were as follows:

- Total length of the rectifying sectioned column:  $1.5 \times N_r$  (tray position) =  $1.5 \times 30 = 45$  ft
- The reflux stream (Light Naphtha), this is found at the 1<sup>st</sup> tray =  $1.5 \times 1 = 1.5$  ft
- The Heavy Naphtha stream, this is found at the 2<sup>nd</sup> tray =  $1.5 \times 2 = 3$  ft

- The Kerosene stream, this is found at the 16<sup>th</sup> tray =  $1.5 \times 16 = 24$  ft
- The Diesel steam that is found on the 24<sup>th</sup> tray =  $1.5 \times 24 = 36$  ft
- The AGO steam that is found on the 30<sup>th</sup> tray =  $1.5 \times 30 = 45$  ft

With a total number of 30 trays, Figure 7 shows a computer aided design of the rectifying section illustrating the tray position with estimated height.

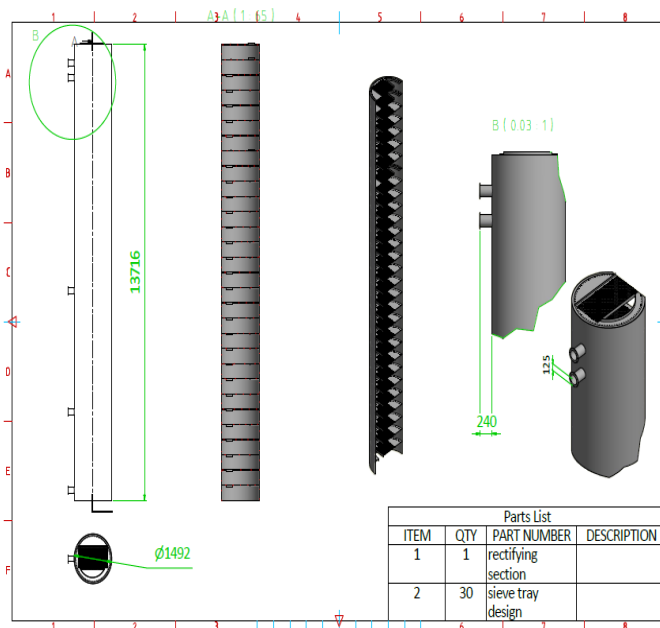


Figure 7: The Interior of Rectifying Section

## Stripping Section

The stripping section of the design providentially possesses the same diametric nature as the rectifying section. It elaborately carries the heavier components left after the AGO production which happens to be the residual crude down the column to the sump. As a matter of material and feed utilization, the stripping section still operating at atmospheric condition could be installed with a submerged combustion approach to raise the temperature to the boiling point of gas oils (supposing the vacuum gas oils) and then channeled out for increasing the marginal profitability.

The remaining height from the schematic distillation unit goes to the stripping unit:

$$\text{Stripping section Height} = 1.5 \times N_s = 1.5 \times 16 = 24 \text{ ft}$$

## Sump /Submerged Section

Since the stripping section would contain the submerged combustion chamber, some portion of the height will be used to accommodate the installation of

sieve trays to aid in the heat and mass transfer of the vaporized atmospheric residue. The introduction of submerged combustion zone to refining processes was originally adopted by (See *et al.*, 1943) for the direct production of asphalt from atmospheric residue totally eradicating the need of a vacuum distillation column.

Submerged combustion is defined as a combustion process that occurs beneath the surface of a liquid. A mixture of the high temperature fuel and air is directly discharged into the atmospheric liquid. This direct contact creates increase in agitation, turbulence, enthalpy and entropy. All these factors help to raise the temperature of the crude to the boiling points of the gas oils that couldn't have been achieved via atmospheric pressure and re-boilers heat alone. The rising vapour is then allowed to pass through packing's and at the right temperatures the products will separate out leaving the residue as asphalt. The direct contact between the hot flue gas and the liquid results in unusually high heat transfer rates and a thermal efficiency of  $\geq 90\%$ .

Figure 8 shows a computer added diagram of the submerged combustion process.

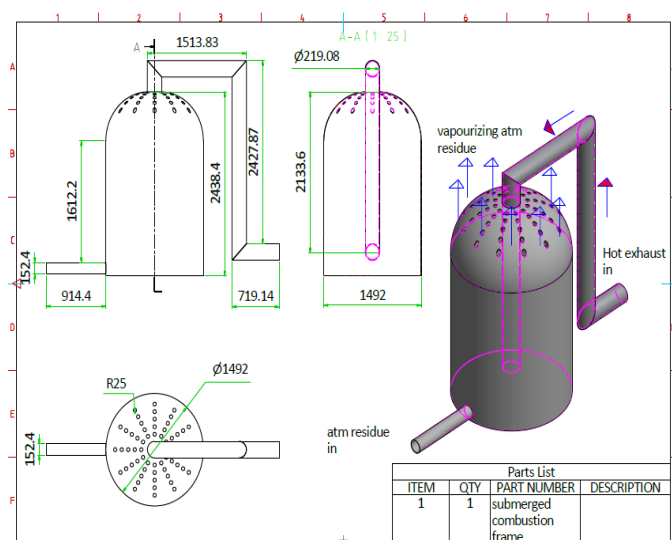


Figure 8: Submerged Combustion Section

## Submerged Combustion Fuel

### *Suitability of Fuel*

Right from the onset of Modular refining technologies, emphasis has been laid on the inability to utilize the atmospheric residue created, since the technology of the submerged combustion have taken care of that, the focus on the fuel type is a thing to bother about. In

several cases, the process fuel type used is LPG but since the bonny medium shows low quantity of off-gas and LPG standing as one of the arms of the profit margin components, it is advised that the fuel type be a low demandable, controllable fuel. From the streams of products, the best fuel to utilize for the submerged combustion is Naphtha. This will inevitable not affect the quantity of other marketable products and thus be used for this sole purpose for the recovery of other heavier components.

To combust Naphtha, they will follow the normal suit of the general hydrocarbon combustion model. If the stoichiometric combustion takes place using air as the oxygen source, the nitrogen present in the air can be added to the equation 4 and 5 to show the composition of the resultant flue gas.

Due to the homogeneity of the naphtha fuel, it would be cumbersome to perform a manual calculation; hence the combustion is performed using Hysys software. In this simulation, the light and heavy naphtha are predominantly mixed in a mixer and then it is then charged in a conversion reactor which acts as the engine as shown in Figure 8. At an optimal scheme, the operating conditions for the air to fuel mixture are highlighted in Table 9.

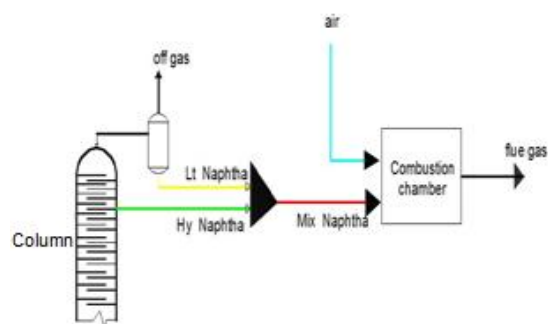


Figure 9: Naphtha Combustion Process

From Table 7, it is noted that the air needed to completely combust the Naphtha fuel comes into the engine at 1.103 bars (110.3 kPa), 25°C (77F) and 0.423 USGPM (3.39  $ft^3/hr$  1.60 litres/min). The corresponding result of the flue gas from the engine leaves at 417.7°C, 100.04 kPa, 1.0924 USGPM (8.76  $ft^3/hr$ ) and most importantly is the heat flow which is  $-2.1717 \times 10^5$  Btu/hr (exothermic). The liquid naphtha is charged in the combustion chamber of the engine through the nozzles and then atomized to effectively creating a larger surface area for combustion to occur.

Table 7: Operating Condition of Flue Gas

CONDITIONS					
Name	Unit	Naphtha	Air	Dummy Liquid	Flue Gas
Vapour		0.065	1	0	1
Temperature	F	129.5064	77	783.8687	783.8686
Pressure	psia	14.5038	16	14.5038	14.5038
Molar Flow	lbmol/hr	2.9015	6.5	0	9.4714
Mass Flow	lb/hr	231.9311	188.175	0	420.1061
Std Ideal Liquid Volume Flow	USGPM	0.6728	0.4273	0	1.0924
Molar Enthalpy	Btu/lbmole	-7.48E+004	-3.914	-2.29E+04	-2.29E+04
Molar Entropy	Btu/lbmole-F	20	28.06	49.97	49.97
Heat Flow	Btu/hr	-2.17E+005	-2.54E+01	0.00E+00	-2.17E+05

The flue gas which now acts as the energy source is submerged into the column where the atmospheric residue is held. Conventionally there will be a heat transfer mechanism occurring due to the different in temperature potential as the heat from the flue gas gradually increases the vapour pressure of the residue counterbalancing with the pressure at the bottom of the column. Hence, the individual components of the atmospheric residue begin to boil gradually, vaporizing to the trays inserted in the column.

Scientifically, the relationships in the submerged chamber are expressed as equation 6 and 7 below: Heat rejected from flue gas is = the heat gained in the atmospheric residue.

$$Q_{flue\ gas} = Q_{Atm, residue} \dots \dots \dots (12)$$

$$Q_{flue\ gas} = hA(t_{fluegas} - t_{atm}) \dots \dots \dots (13)$$

Where Q = heat rejected or gained, h = convective heat transfer coefficient of the flue gas, A = area of the liquid covered,  $t_{fluegas}$  = temperature of the flue gas and  $t_{atm.resid}$  = atmospheric residue temperature.

From the simulation carried out on the engine with the cross section of the column taken, we can determine the convective heat transferring coefficient of the flue gas in conjunction with the area of the atmosphere residue to provide us with the overall heat transfer coefficient

$$\frac{Q_{flue\ gas}}{(t_{fluegas} - t_{atm})} = hA$$

$$hA = \frac{2.1717 \times 10^5}{783.86 - 645.30}$$

$$hA = 1567.67 \text{ Btu/hr/F}$$

This shows the convective overall potential of the flue gas using Naphtha as the feed fuel under a complete combustion scenario.

### Hysys Simulation of the Integrated Distillation Column

Another simulation with same operating conditions as earlier used was carried out for the entire integrated distillation column as shown in Figure 10. The engine flue gas and the atmosphere residue both enter the column as described. This increases the temperature, vapors pressure and entropy of the atmosphere residue and then vaporizes the different components present in the atmospheric residue. This subsequently increases the temperature of the product cuts coming out of the column. The column consists of a 16 tray column which is to add up to the 31 trays at the rectifying section to make it a total of 46 trays. It should be noted that a re-boiler with the same heat flow of  $2.1717 \times 10^5$  Btu/hr as gotten from the engine flue gas was used.

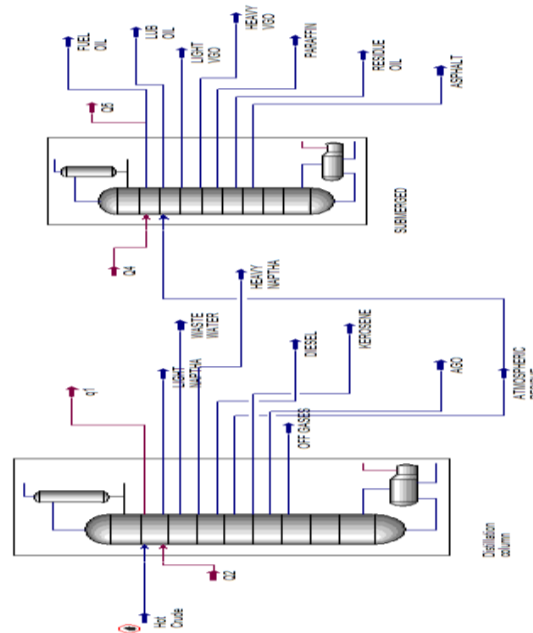


Figure 10: Hysys Simulation of the Integrated Distillation Column



Figure 11 shows a process flow diagram of the stripping and submerged combustion process while Table 8 gives a summary view of the flow rate, temperature and the tray position of the products coming out from the integrated distillation column

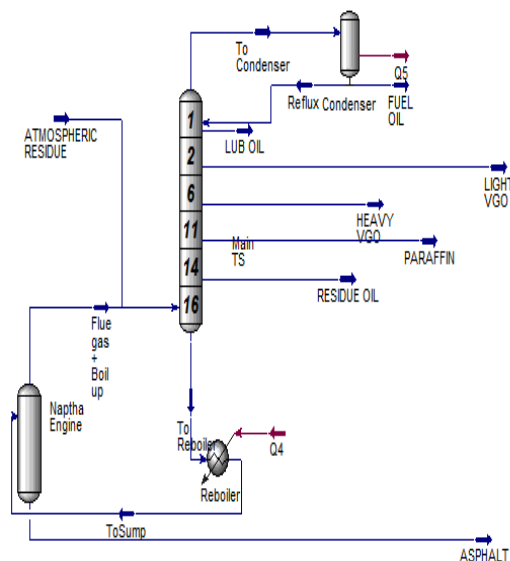


Figure 11: Process Flow Diagram of the Stripping and Submerged Combustion Process

Table 8: Profile of Distilled Products

Products	Volumetric Flow Rate (ft <sup>3</sup> /hr)	Tray Position	Temp.(°C)	ASTM (°C)
Off Gas	369.97	1	46.29	0-30
Light Naphtha	3.890	1	46.29	30-100
Heavy Naphtha	1.507	2	76.53	80-200
Kerosene	730.13	16	139.13	170-280
Diesel	812.49	24	273.67	220-320
AGO	170.16	30	340.02	290-350
Fuel Oil	590.65	31	297	
Lube Oil	190.97	31	374	350-575
LTGO	150.07	32	399.8	
HTGO	0.000000539	36	419	345-565
Paraffin	0.0000150	41	422.2	>370
Residue	0.0000152	44	427.7	565-580
Asphalt	377.14	46	482.1	>580

## CONCLUSION

The Integrated distillation column successfully brought out all distilled products under atmospheric conditions thereby eliminating the need of a vacuum distillation column while the Naphtha was successfully used as the

source of fuel for the combustion process. The application of submerged combustion technology to refining for maximum product recovery, the total eradication of the need of an additional column, re-boiler, condense, ejectors used in a vacuum distillation process and the channeling of both atmospheric residue and Naphtha for better utilization were the additions to knowledge by this study. Further research into this technology would be necessary through the construction of pilot plants in learning institutions and collaboration between the industry and academia for appropriate application.

## CONFLICT OF INTEREST

None declared.

## ABBREVIATIONS

NNPC	- Nigerian National Petrochemical Corporation
LPG	- Liquefied Petroleum Gas
bpd	- barrels per day
SG	- Specific Gravity
AP	- American Petroleum Institute
<i>F</i>	- Volumetric Flow Rate
<i>M</i>	- Mass Flow Rate
SM	- Sulphur Mass Flow Rate
SC	- Sulphur Content
USGPM	- US Gallon per Minute
lbmol	- pound mol
<i>ft</i>	- Feet
kPa	- kilopascal
<i>N<sub>s</sub></i>	- Number of Trays
LTGO	- Low Temperature Gas Oil
HTGO	- Heavy Temperature Gas Oil
Btu	-British Thermal Unit
Psia	-Pounds per Square Inch Absolute

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**Article's citation:**

Mamudu OA, Igwe GJ, Okonkwo E and Okocha SI (2016). Modular crude oil topping refinery: The total utilization of all distilled cuts. *Ew J Petrochem Res Innov* 1(2): 7-16.