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# Investigation of Naphtha Hydrotreating (NHT) Unit Exergy Utilization: A Case Study of a Petrochemical Industry in A developing Country

K.F. Oyedeko, O. D. Ogunjimi, A.A. Adesina

***ABSTRACT***

**The need for efficient energy use in refinery operations is the proffered solution to the poor management of energy resources which has resulted in the instability in oil products prices, irregular plant shutdowns experienced in refineries of developing countries and increased carbon emission to the atmosphere. This research work aims to carry out exergy analysis on major energy consuming units which will aid in determining sites and causes of primary energy losses and proffer solutions to maximizing energy utilization. The Naphtha Hydro-treating (NHT) unit of the case model refinery was successfully simulated using Aspen Hysys. The analysis revealed more than half (51.9 %) of the input exergy was lost to the environment and an irreversibility of 32.7% occurred in the Stripper column. Comparison was also made with the same unit at Kaduna refinery and petrochemical plant and the results showed a conversion efficiency of about 91.28% when compared to 44.35% from the old refinery though this could be attributed to factors like age of plant, inadequate maintenance etc. The positive value of the amount of heat recovered from that of the flue gas in the boiler and furnace gave an opportunity to recover the energy lost and integrated back to the system for economic viability of the plant which result in a payback period that is less than a year.**

**Keywords:** Aspen HYSYS, exergy performance, hydrotreating, naphtha, refining.

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## I. Introduction

One of the important aspects of improving the quality of life for sustainable development and reducing poverty is energy. The energy requirement is an essential element and a critical factor for the economic growth of any nation that cannot be overemphasized. The increasing requisition for industrialization of countries in the world has consequently put the demand and utilization of energy on the high pedestrian [1], [2].

In developing countries such as Nigeria, the proportion of energy consumption globally is projected to increase from 46 to 58 % between 2004 and 2030, at an average annual growth rate of 3%. While during the same period industrialized nations such as the USA, will witness annual energy demand growth of 0.9 % [2]-[4].

The effective management of energy in industrial processes is very vital for sustainable and economic development. The utilization of process integration can be an effective means of managing energy effectively, especially in an industrial process system. An important aspect of process integration that has been used and essential is the Exergy utilizing investigation [2], [5]-[7].

Exergy investigation is used as an effective thermodynamic method using the principles of conservation of mass and energy in a specified environment for the evaluation of the energy efficiency of a process [5]. Exergy analysis may be used in the early development stage of a new process and guidelines for more effective use of energy in the existing plant. Additionally, more significant pointer than the conventional energy, efficiency can be defined using exergy; so the degree of exactness can be observed for a process by the calculation of exergy efficiency [2], [6]-[8].

There is a need to improve the energy system of a company to remain competitive as energy consumption influences production cost. The instability in prices of oil, poor management of most developing countries' refineries and petrochemical companies due to poor management of material and energy resources, becomes an essential factor to keep the refineries and petrochemical company functioning.

The Naphtha Hydrotreating (NHT) Unit is an important aspect of the refinery that consumes a lot of energy-requiring good energy management and policy [2], [9]-[13]. The Naphtha Hydrotreating Unit, NHT is a catalytic refining process that is designed for the removal of S, N, Hg and metallic compounds as well as saturation of olefins with a turndown capacity of 50%. It generates feed for the Isomerization unit, Continuous Catalytic Reforming unit and also generates $H_2$ rich gas for use in the refinery. These reactions are mainly from these processes; desulphurization, denitrification and hydrogenation reactions [10]-[15]. Investigation of the NHT unit can be used to determine the location and magnitude of energy loss [8]

### A. Process Route Description

The feed from the refinery mainly raw Naphtha (NHT-FEED) at a temperature of 63 °C and pressure of 3.5 kg/cm$^2$entered into a Surge Drum 151-W-1001.and the bottom entered into Pump 151-PA-1001 A/B. The fluid was charged using the pump to a mixer 151-MX where it mixed with a fresh Hydrogen-Feed, gas stream at high pressure and temperature of 67°C. This was pumped into an Exchanger of Combined Feed (151EE-1001A-N) to be preheated by the products of the reactor from a temperature of 65 °C to 292°C. The preheated stream temperature was increased by heating it to the desired reaction temperature of 334 °C by Heater (151-FE-1001) and then entered into the Reactor 151-RB-1001 in which the following reactions; hydro-desulphurization, hydro-denitrogenation, hydrodeoxidation and olefin saturation occurred with respective following products of Hydrogen Sulfide ($H_2S$), Ammonia ($NH_3$), Steam ($H_2O$) and Cyclohexane ($C_6H_{12}$) obtained. The products of the exothermic reactions at a temperature of 343°C were passed through the tube side of the Exchanger of combined Feed (151EE-1001A-N) to pre-cool the product stream simultaneously preheating the reactant incoming fluid stream. The product from the Exchanger of combined feed was left at a temperature of 235 °C and was allowed to cool to a temperature of 75 °C in Products Condensers 151-EA-1001A-P. The condensed product was channeled to a Separator 151-W-1003. In which the sour $H_2$ gas (vapour phase) moves from the top of the separator and entered the Recycle Compressors 151-KA-1001 A/B, from where a part of this gas is sent to CFE in which part of it is used as makeup-hydrogen for the reactions.

On the other hand, the liquid obtained from the bottom of Separator 151-W-1003 was channeled to the Stripper 151-CC-1001 at a temperature of 49 °C, through a Pump (151-PA-1006 A/B). Off gas and unstabilized LPG respectively from the top and bottom of the Stripper receiver were sent to the SGC unit. The treated naphtha from the bottom of Stripper 151-CC-1001 was sent to Splitter 151-CC-1002 to divide the bottom product from the Stripper to give two products; Light Naphtha and Heavy Naphtha[1], [2].

## II. Materials and Methods

### A. Operating Data

Operating Data consist of Temperatures, Pressures, Stream Compositions, and Flows. The data for the Piping and Instrumentation Diagram of the Naphtha Hydrotreating (NHT) Unit was obtained from the case model [10]-[12]. The process simulation using Aspen HYSYS version 8.6 [16] was done using data extracted from the laboratory model manual[10]-[12] of the model. The data comprises compositions for the feed, stream pressures, temperatures, mass flow rates and those required for piping and instrumentation of Naphtha Hydrotreating unit.

### B. Process Simulator and Modeling of NHT

The processes taking place in the Naphtha Hydrotreating plant as shown in the flow sheet (PFD) include the following standard unit operation blocks and logical units (e.g. Heaters, Reactor, Heat-exchanger, Coolers, Separators, Columns etc.). These were modelled and simulated using a sequential process software - Aspen HYSYS Version 8.6.

### C. Exergy Calculations

Microsoft Excel of the Microsoft Office Suite 2013 package was used to calculate the exergy entering and exiting, the irreversibility then the exergy efficiency of some selected components of the Naptha Hydrotreating Unit. The Microsoft Excel of Microsoft Office was used for calculating the following parameters: Inlet and Outlet streams temperatures, molar flow rate enthalpies and entropies, which were extracted from the simulation of the streams entering and leaving the equipment. The temperature 25 °C, enthalpy and entropy -28990KJ/Kg mole and 209.3KJ/Kg mole°C were used respectively for the reference environment properties. Equations given by [17] were used to calculate performance parameters for the following selected units Pumps (151-PA-1001AB and 151PA-1006AB), a Heat exchanger (151-EE-1001A-N), Reactor (151-RB-1001AB), Compressor (151-KA-1001A/B), Separator (151-W-1003), Stripper and Splitter columns (151-CC-1001 and 151-EE-1006), Surge Knockout drum (151-W-1001), Heater (151-FE-1001A-N), Cooler (151-EA-1001A-P)[2]. The obtained results were tabulated.

### D. Heat Recovery

Major Exergy destruction and heat recovery through flue gas and the use of Nano fluids in equipment were considered using expressions given by [18], [19]. In comparison with estimates by [20]-[22] the cost-effectiveness was also obtained.

## III. Results and Discussion

The simulated and modelled NHT unit using Aspen HYSYS version 8.6 software is shown in Fig. 1.

### A. The Efficiency of the Unit

The results of exergy calculations of the Naphtha Hydrotreating (NHT) Unit are presented in the Tables below. The inlet and outlet exergies with the irreversibility for each piece of equipment are shown in Table I. While Table II is the Exergy efficiency of the equipment. The Reactor has 82.4 %, Heat Exchanger, 83.1 % and the Compressor 90.9 % exergy efficiencies respectively. It was noted that a large amount of the energy that entered the heat exchanger was dissipated to heat within the process [2], [23].

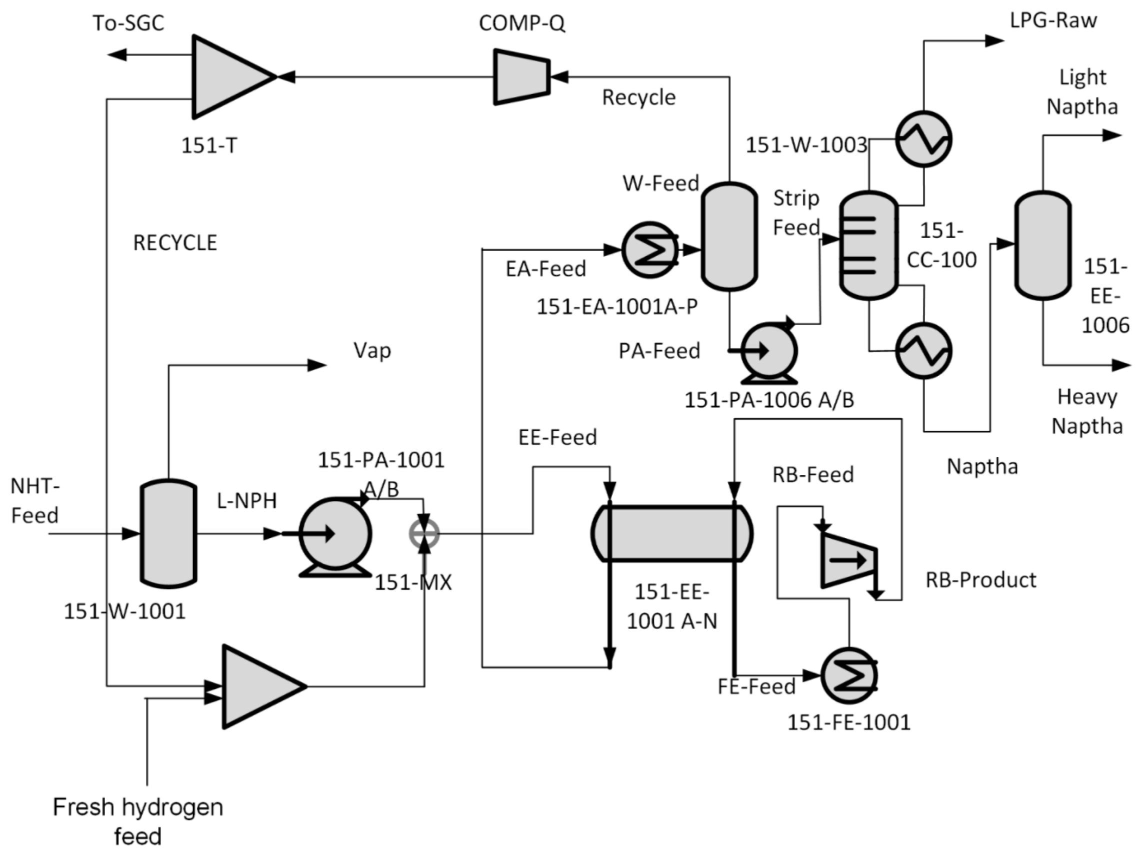


Fig. 1. Flow Diagram for Simulation of Naphtha Hydrotreating (NHT) Unit.

Similarly, high exergy efficiency of 84.7 % was found in the Separator while efficiencies of 73.9 % and 92.9 % were respectively observed for Pumps 151-PA-1006 and 151-PA-1001. Interestingly, Heater 151-FE-101 had a low efficiency of 30.2 % and recorded a high value of irreversibility. The high loss of heat in the furnace indicates its inefficiency. The effect of this is depletion of fossil fuel due to an increase in the use of fuel for more energy resulting in an increase in carbon emission and contributing to the environmental pollution problem. Process modifications of the temperature of hot and cold stream in the Heater can be explored to reduce the heat losses and low efficiency of this unit thereby improving the efficiency by increasing the heat recovery in the preheat train [2], [23]

The Splitter and Stripper columns had efficiencies of 85.0 % and 22.5 % respectively. Exergy losses in columns could be associated with the separation process occurring in the column giving rise to high entropy. The process involves loss of momentum as a result of mass transfer and thermal losses respectively and pressure drop driving force due to mixing of fluids and temperature driving force in the column [24].

## B. *Exergy Destruction (loss)*

Exergy destruction (losses) occurred in the units mostly accrued from the resistance and friction losses as a result of the fluid flowing unit and making contact with the wall. This effect is small in the following units Reactor, Compressor, Pumps and low-Pressure separator [2], [19]. However high exergy losses were observed in the following equipment Stripper and Heater having a High irreversibility or destruction of 11724008.13 and 1771113225.5 KJ/hrespectively, with the respective contribution to irreversibility given as 32.7% and 51.9 % of the entire lost work as presented in Table III. The entropy generation owing to temperature variations and drop in pressure resulted in exergy losses which were attributed to high lost work in the stripper column. Low energy efficiencies are reportedly associated with fractionators [2], [23].

## C. *Results Validation*

The validation of the results of this model was done by comparing the observations of similar studies on the hydro treatment process with another Refining and Petrochemical Company NHT unit at Kaduna; a refinery that has been running for years.[2]. The comparison is presented in Table 3, showing a difference of 36.3 % and 31.5 % exergy efficiency respectively in the Splitter and Heat exchanger, with that of the current study being the better of the two. Similarly, differences of 26.5 % and 0.9 % were observed in the efficiencies of the Compressor and Stripper column respectively, with those of the current study found to be more efficient. Contrastingly, differences of 5.4 % and 1.9 % were observed in the efficiency of the Reactor and Separator respectively with that of the KRPC model found to be more efficient. The lesser efficiencies observed inmost of the equipment of the NHU of KRPC compared to those of NHU in the present study can be attributed to the equipment age and inadequate maintenance of the earlier. The current model observed 91.28 % conversion in thedesulphurization reaction, more than twice an observation of 44.35 % reported by a study that modelled the Hydrodesulphurization Unit of KRPC [2].

TABLE I: RESULT OF EXERGY CALCULATIONS

| Component | Exergy In (KJ/h) | Exergy Out (KJ/h) | Irreversibility (KJ/h) |
|---|---|---|---|
| Pump (151-PA-1001AB) | 46358771.30 | 43075756.80 | 3283015.45 |
| Exchanger (151-EE-1001 A-N) | 41811194.25 | 34746039.00 | 7065155.25 |
| Heater 151-FE-1001 | 253664415.00 | 76553092.50 | 1771113225.50 |
| Reactor 151-RB-1001 | 9275909.25 | 7638817.5 | 1637091.75 |
| Cooler 151-EA-1001 | 39597381.41 | 31750147.5 | 7847233.91 |
| Separator 151-W-1003 | 78688479.73 | 66672252.5 | 12016227.23 |
| Compressor 151-KA-1001 | 3214487.50 | 2920591.50 | 293896.00 |
| Pump 151-PA-1006 | 59726184.20 | 44121622.90 | 15604561.30 |
| Stripper 151-CC-1001 | 144121622.90 | 32397614.80 | 111724008.13 |
| Splitter 151-EE-1006 | 31241625.00 | 26543666.32 | 4697958.68 |
| Total | | | 341280470.20 |

TABLE II: EXERGY EFFICIENCY AND CONTRIBUTION TO EXERGY LOSSES (IRREVERSIBILITY)

| Component | Exergy Efficiency (%) | Contribution to Irreversibility (%) |
|---|---|---|
| Pump (151-PA-1001AB) | 92.9 | 1.0 |
| Exchanger (151-EE-1001 A-N) | 83.1 | 2.1 |
| Heater 151-FE-1001 | 30.2 | 51.9 |
| Reactor 151-RB-1001 | 82.4 | 0.5 |
| Cooler 151-EA-1001 | 80.2 | 2.3 |
| Separator 151-W-1003 | 84.7 | 3.5 |
| Compressor 151-KA-1001 | 90.9 | 0.1 |
| Pump 151-PA-1006 | 73.9 | 4.6 |
| Stripper 151-CC-1001 | 22.5 | 32.7 |
| Splitter 151-EE-1006 | 85.0 | 1.4 |
| Total | | 100 |

TABLE III: COMPARISON OF MODEL PREDICTIONS WITH A COMPANY DATA

| Variables | The Model | KRPC Model | Difference |
|---|---|---|---|
| Efficiency (%) | | | |
| Heat Exchanger | 83.1 | 51.6 | 31.5 |
| Heater | 30.2 | 23.9 | 6.3 |
| Reactor | 82.4 | 84.3 | 1.9 |
| Cooler | 80.2 | 79.8 | 0.4 |
| Separator | 84.7 | 90.1 | 5.4 |
| Compressor | 90.9 | 64.4 | 26.5 |
| Stripper | 22.5 | 21.6 | 0.9 |
| Splitter | 85.0 | 48.7 | 36.3 |
| Sulfur Removal Conversion (%) | 91.28 | 44.35 | 46.93 |

### *D. Revamp of Energy*

An investigation of the energy utilization of the components revealed that the overall exergy efficiency of the Naphtha hydrotreatment (NHT) unit process was contributed by the Heater (151-FE-1001) and Stripper (151-CC-100). It was also observed that there is high wastage in energy utilization with subsequent high potential for revamp of energy due to low efficiencies that resulted in Heater (151-FE-1001) and Stripper (151-CC-100) respectively contributions of 51.9 % and 32.7 % (totaling 84.6 %) of total irreversibility observed; consequently, the revamping of these two equipment was a focused for heat recovery through the flue gasses.

### *E. Furnace*

The HNT unit furnace is another equipment in which a large amount of energy is lost due to the flue gas from its symbols by en-dashes; for example, “NiMn” indicates the intermetallic compound $Ni_{0.5}Mn_{0.5}$ whereas “Ni–Mn” indicates an alloy of some composition $Ni_xMn_{1-x}$.

The flue gas average temperature is about 335 °C. One of the ways to increase the efficiency of the furnace is to recover part of the heat from the flue gas. The means of recovering heat can be done by passing flue gas through a heat exchanger that is placed before the furnace. Then, the heat recovered can be used as means of preheating the combustion air thereby saving the energy used. Equation (1) can be used to express Heat recovery from flue gas [18].

Rate of heat recovered, $Q_r = m_g \times c_p \times \Delta T_d$ (1)

Where $m_g$ = flue gases mass flow rate for heat recovery
$C_p$ = specific heat of flue gas and
$\Delta T_d$ = temperature drop of the flue gases.

Calculation of the annual fuel savings associated with it can be done using the heat recovery:

$$\text{Fuel savings} = \frac{Qr}{H_{ff}} \;.\,. \quad (2)$$

The annual fuel cost savings can be calculated as:

Annual cost savings of fuel = Annual Energy Savings × Price (3)

Equation (4) can be used to calculate the payback period for different energy-saving strategies [25].

$$Payback\ period\ (yr) = \frac{\text{Incremental cost}}{Annual\ cost\ savings} \quad (4)$$

Using the mean temperature of flue gas as 335 ºC, the allowable minimum stack gas temperature as 120 ºC and 215°C as the achievable reduction in temperature for the flue gas. The rate of heat recovered from flue gas is about 11.9 MJ/h. Assuming the heat content in the fuel is about 46.1MJ/kg, the fuel-saving is 2.5 litres/h. The operation of the furnace is assumed to be about 3780 h/yr, hence the fuel-saving is 9,450 litre/yr and the fuel cost saving at $ 0.38/litre is $3,591/yr. By taking the cost of the heat recovery system of the furnace as $512.04, the cost can be recalculated for 2021 thus

$$Cost\ in\ 2021 = \frac{\text{Index for 2021}}{index\ for\ 2010} \times cost\ in\ 2010 \quad (5)$$

$$Cost\ in\ 2021 = \frac{317.0}{153.5} \times 512.04$$
$$= \$\ 1{,}057.43 Payback\ period$$
$$= \frac{1{,}057.43}{3591} = 0.29\ \text{yr}$$

Hence, the cost of a heat recovery system can be recovered in less than 4 months. If the payback periods are less than one-third of the system life, it is indicated that the implementation of the system is very cost-effective [22]. Considering the case study plant uses modern burners which can withstand much higher combustion preheated air, it is feasible to use a heat recovery system to preheat the combustion air in the exit of the flue gas. Fuel consumption can be reduced up to about 25% by using the preheated air at a high temperature of about 1327°C.

*F. Column*

The flue gas temperature leaving the boiler is in the range of 150–250 °C, as all the heat produced by burning fuel cannot be transferred to water or steam in the boiler. A large amount of heat energy is lost through flue gases of which about 10–30 percent of the heat energy is lost during this period. Therefore, recovering part of the heat from the flue gas can help to improve the efficiency of the boiler. Heat can be recovered from the flue gas by passing it through a heat exchanger that is installed after the boiler, the recovered heat can be used to pre-heat boiler feed water, combustion air and this will save the energy use. The flue gas is usually at a high temperature to ensure that it is enough to pre-heat the fluid.

The temperature of Boiler flue gas can be reduced by using nanofluids [19] carried out an analysis of a boiler flue gas temperature reduction procedure using nanofluids. Considering the boiler has a capacity of about 3000 kg/h with a fuel flow rate of 160 liters/h and flue gas temperature of 335°C. Since the minimum allowable stack temperature of natural gas is 120 °C, the reduction in temperature for the flue gas that can be achieved is about 215°C. Taking the density of natural gas as 800 kg/m$^3$, the amount of fuel used is 128 kg/h and the air-fuel ratio is about 15:1, the amount of combustion air is approximately 15 times the weight of fuel thus:

Amount of combustion air = 15 x 128 =1920 kg/h.

Total mass of flue gas =1920 + 128 kg/h =2048 kg/h = 0.57 kg/s

Using the specific heat capacity of flue gas as 1.1 kJ/kgK, Using (1) to calculate the amount of heat recovered:

Heat recovered = 0.57kg/s x 1.1 kJ/kgK x 215°C = 134.805 kJ/s = 57.8 x 3600 = 485.298 MJ/h

Assuming the heat content in the fuel is about 47 MJ/kg, the reduction in fuel usage is

$$\frac{485.298\ MJ/h}{47\ MJ/kg} = 10.325\ kg/h$$

$$\frac{10.325\ kg/h}{0.8\ kg/litres} = 12.907\ litre/h$$

A boiler is operated for about 7920 h/yr, hence, the fuel-saving for one year is

$12.907\ litres/h\ x\ 7920\ h/year = 102{,}223.4\ litre/yr$

Using the price of fuel as $0.38/litre, then:

$$Cost\ Saving = 102{,}223.4 \frac{litre}{yr} x\ \$\ 0.38/\text{litre}$$
$$= \$\ 38{,}844.89/yr$$

By using the cost of a heat recovery system in a boiler as around $11,840.84, the cost in 2021 is calculated using (5) as follows:

$$cost\ in\ 2021 = \frac{317}{153.5} \times 11{,}840.84 = \$\ 24{,}453.07$$

Payback period is calculated using Equation (4) [23], [25]:

Payback period = $\frac{24{,}453.07}{38{,}844.89} = 0.62\ yr$

The cost of recovering heat from a boiler heat system can be done in less than 8 months, using this method. The present study also focused on revamping heat from flue gas as a major contributor to irreversibility. The heat recovery system of the flue gas showed that it is economically viable with a payback period of 4 months and 8 months for the Heater and in the Column respectively.

## IV. Conclusion

A thermodynamic analysis through exergy calculations of Naphtha Hydro treatment unit of case model refinery was presented in this study with the application of Aspen HYSYS version 8.0 software. The major inefficiency in the systems was identified and more than half (51.9 %) of the exergy losses occurred in the Heater. Next to it was in which the energy losses to the environment occurred in the Stripper column at 32.7 % of the exergy losses while the remaining equipment considered contributed to the rest exergy losses. A payback period of about a year was considered and found to be economically viable as a result of the heat recovery system from the boiler and flue gas from the furnace. To reduce the temperature of the flue gas, it is recommended to use nanofluids. Moreover, the installation of Heat Exchanger Networks (HENs) makes the energy integration to improve the energy utilization by a reduction in the exchanger loads and exergy losses.

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