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Exergy analysis of Naphtha Hydrotreating Unit (NHU)

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Abstract. The aim of this research work is to develop an exergy analysis of Naphtha Hydrotreating Unit of the Kaduna Refinery and Petrochemical Company (KRPC). This was achieved through extraction of data from the Laboratory operating manual and the process flow diagram of the naphtha hydrotreating unit of the refinery which is used in the simulation; the site of primary exergy destruction was also determined. The major components of exergy efficiencies of the major component were determined. Also the potential for process improvement through revamp was determined. Exergy analysis of Naphtha Hydrotreating Unit (NHU) of the Kaduna Refining and Petrochemical Company was successfully simulated using Aspen HYSYS. Exergy efficiencies were found to be very low in Heaters 11H01 and 11H02 at 23.9% and 50.0% respectively. Similarly low efficiencies were respectively observed in Columns 11C02 and 11C01 at 48.7% and 52.8%. The major contributors to exergy destructions were found to be Column 11C01 and Heater 11H01 with percentage contribution of 21.6% and 14.6% respectively, totaling 36.2% of the total irreversibility recorded in the NHU process. Heat recovery from flue gas in the furnace and boilers was considered and found to be economically viable with a payback period of less than one year.

Keywords: Exergy, Aspen Hysys, Heater, NHU, Column

1.0 Introduction

Energy is central to sustainable development and poverty reduction efforts. It is important to our safety, quality of life and also a critical aspect of any nation economic growth. The fast drive for global industrialization has therefore placed the demand for energy on the high [1]. Between 2004 and 2030, global energy consumption proportion is projected to increase from 46 to 58%, at an average annual growth rate of 3% in developing countries such as Nigeria. Industrialized nations during this period, will witness annual energy demand growth of 0.9% [2,3].

The Energy Information Administration (EIA), a statistical agency of the U.S.A Department of Energy projections, shows that fossil fuels will remain as primary sources of energy in immediate future. Thus, along with the development of alternative energy sources, effort must be made to seek modus operandi that will minimize the damage caused by the fossil fuels. Initiatives like cleaner production and zero emissions are important approaches in this regard



[2]. However, another short term solution has to do with improving energy efficiency in industrial processes via process integration. An approach that has contributed to process integration is the exergy analysis [4]. Maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment is called Exergy. Unlike energy, exergy is not subject to a conservation law (except for reversible processes). Rather, exergy is consumed or destroyed due to irreversibilities in any real process. Exergy consumption is proportional to the entropy created during a process. The quality and quantity of the energy involved in transformations within a system is measured by Exergy. Thus, Exergy analysis, also called lost work analysis can be a helpful tool in the evaluation of the energy efficiency of a process [4].

The Naphtha Hydrotreating Unit (NHU) of the Kaduna Refining and Petrochemical Company (KRPC) is designed to provide suitable feed, treated heavy Naphtha cut of sulfur content less than 1.00 ppm for the Catalytic Reforming Unit (CRU). The process is a sweetening process involving removal of impurities, like sulfur, nitrogen, oxygen etc, that constitute catalyst poison in the presence of a catalyst. Therefore major reactions include; desulphurization, denitrification and hydrogenation reactions [5]. Considering the negative effects of the instability in prices of oil, regular shut down of our Refineries and Petrochemical Companies due to poor management of material and energy resources, efficient energy use in the operations of the refineries becomes a key factor to be considered when making decisions to keep the refineries functioning. NHU is a major energy consuming unit of a refinery and therefore requires extensive energy management. Carrying out an Exergy analysis on this unit will help to determine sites and causes of primary energy loss and also aid decision making by providing meaningful information when assessing the performance of energy systems [6,7].

Aspen HYSYS is a tools combination which is used for estimating the physical properties and liquid-vapour phase equilibrium of various in-built components. These components are the substances that are used within the plant as feeds, within the reaction and separation sections [8]. The program is such that it converge both energy and material balances and has standard unit operations typical of any processing plant. The software updates the calculations as the user enters information and does it as fast as it can. The successful completion of an operation is seen by the changes in colour on screen [9]. ASPEN HYSYS version 8.0 was used to carry out the simulation of Reactor section of NHU of the Kaduna Refining and Petrochemical Company (KRPC) using information extracted from the Laboratory Operating Manual and Process Flow Diagram while existing exergy equations were used to determine exergy efficiencies, sites of primary destruction and potential for revamp using Microsoft Excel. The equipment selected for exergy analysis includes Heat Exchanger, Heaters, Reactor, Coolers, Separators, Columns and Surge Drum [10].

2.0 Materials and Methods

2.1 Data Extraction

Operating Data (Stream Compositions, Temperatures, Pressures and Flows), Piping and Instrumentation Diagram were collected from the NHU of the KRPC. A thorough study of the process flow diagram, feed and products were carried out in order to extract all the necessary and available information required to carry out the process simulation of the NHU of the refineries. The feed compositions from the laboratory manual were used to characterize the oil

while the stream temperatures, pressures, and mass flow rates were extracted to carry out the process simulation using Aspen HYSYS version 8.0.

2.2 Modeling of NHU in a Process Simulator

Simulation of the Fluid Catalytic Cracking Unit was carried out using Aspen HYSYS Version 8.0, which is a sequential process in the modeling and simulation software. The flow sheet (PFD) (Figure 1) includes a library of standard unit operation blocks and logical units (e.g. Heaters, Reactor, Heat-exchanger, Coolers, Separators, Columns etc.), which represent processes taking place in an actual Naphtha Hydrotreating Unit plant.

2.3 Process Description

Raw Naphtha stream from refinery at a temperature of 39 °C and pressure of 2 kg/cm² was passed into a Surge Drum 11D05. Light gasses still present in very small quantities were sent off through the vent while the liquid Naphtha from the bottom of 11D05 was sent to Pump P-100. The fluid was charged by the pump to a mixer 11M01 where it mixes with a fresh hydrogen gas stream (H-Feed) at high pressure and temperature of 57.38 °C. The mixture was charged into a combined feed exchanger 11E01A-C where it was preheated by the products of the reactor from a temperature of 41.54 °C to 177 °C. The preheated fluid was then heated to a desired reaction temperature of 335 °C by Heater (11H01) before being charged into the reactors. To achieve detailed conversion in the various reactions that take place in the Hydrodesulphurization process, four Plug Flow Reactors (11R01, 11R02, 11R03 and 11R04) were installed respectively for hydrodesulphurization, hydrodenitrogenation, hydrodeoxidation and olefin saturation reactions with respective products of Hydrogen Sulfide (H₂S), Ammonia (NH₃), Steam (H₂O) and Cyclohexane (C₆H₁₂). The products of the exothermic reactions at a temperature of 335 °C was then passed through the tube side of the previous Heat Exchanger 11E01 so as to pre-cool the product fluid while preheating the incoming reactant stream. The product left the Heat Exchanger at a temperature of 235 °C. The product was cooled in an Air Fin Cooler 11A01 to a temperature of 150.0 °C before being sent to a Trim Cooler 11E02 and cooled to a temperature of 50.0 °C. The product of the Trim Cooler was flashed into a high pressure Separator 11D06. The vapour phase (sour H₂ gas) leaves the top of the drum to a Compressor 11K01. Using a Tee (11T01), a part of this gas is sent to Kerosene Hydrotreating Unit (KHU) as make up gas while the other part of the gas is sent to the Gasoline Hydrotreating Unit (GTU). Some of the Hydrogen recovered is used as makeup-hydrogen for the reactions. The liquid from the bottom of the High Pressure Separator is channeled to a Cooler 11E05 to further cool the liquid before being sent to a Low Pressure Separator 11D07. The bottom product of the Low Pressure Separator was sent to the Stripper 11C01 through a Pump 11P05A/B for Liquid Petroleum Gas (LPG) recovery and Catalytic Reform Unit (CRU) stabilizer vapour distillate. The bottom of 11C01 is heated in Heater 11H02 and sent to a Splitter 11C02 to split the bottom product of 11C01 to Light Naphtha and Heavy Naphtha.

2.4 Exergy Analysis

Exergy in and out, irreversibility and Exergy efficiency of the selected components of Naphtha Hydrotreating Unit were calculated using Microsoft Excel of the Microsoft Office Suite 2013 package. The parameters extracted from the simulation to Microsoft Excel for calculations include; Molar flow, Inlet and Outlet streams temperatures, enthalpies and entropies. These parameters were extracted from each of the streams entering and exiting the equipment. The reference environment temperature, enthalpy and entropy were 25°C, -28990 KJ/Kgmole and 209.3 KJ/Kgmole°C respectively. The units selected for analysis were

Knockout drum (11D05), Heaters (11E01 and 11E02), Pumps (11P01 and 11P02A-B), Heat exchanger (11E01A-C), Plug Flow Reactors (11R01, 11R02, 11R03 and 11R04), Air Fin Coolers (11A01 and 11A02), Trim Coolers (11E02 and 11E05), Compressor (11K01), Separators (11D01 and 11D04), Stripper and Splitter columns (11C01 and 11C02). Using Microsoft Excel of Microsoft Office Suite 2013, equations given by [11] were used to calculate performance parameters and results were tabulated.

2.5 Recovery

Heat recovery through flue gas and use of nanofluids in equipment with major primary exergy destruction was considered using expressions given [12,13]. Cost effectiveness was established in comparison with estimates by [14,15].

3.0 Results and Discussion

The modeled NHU unit in the simulation environment of Aspen HYSYS version 8.0 Software is as shown in Figure 1.

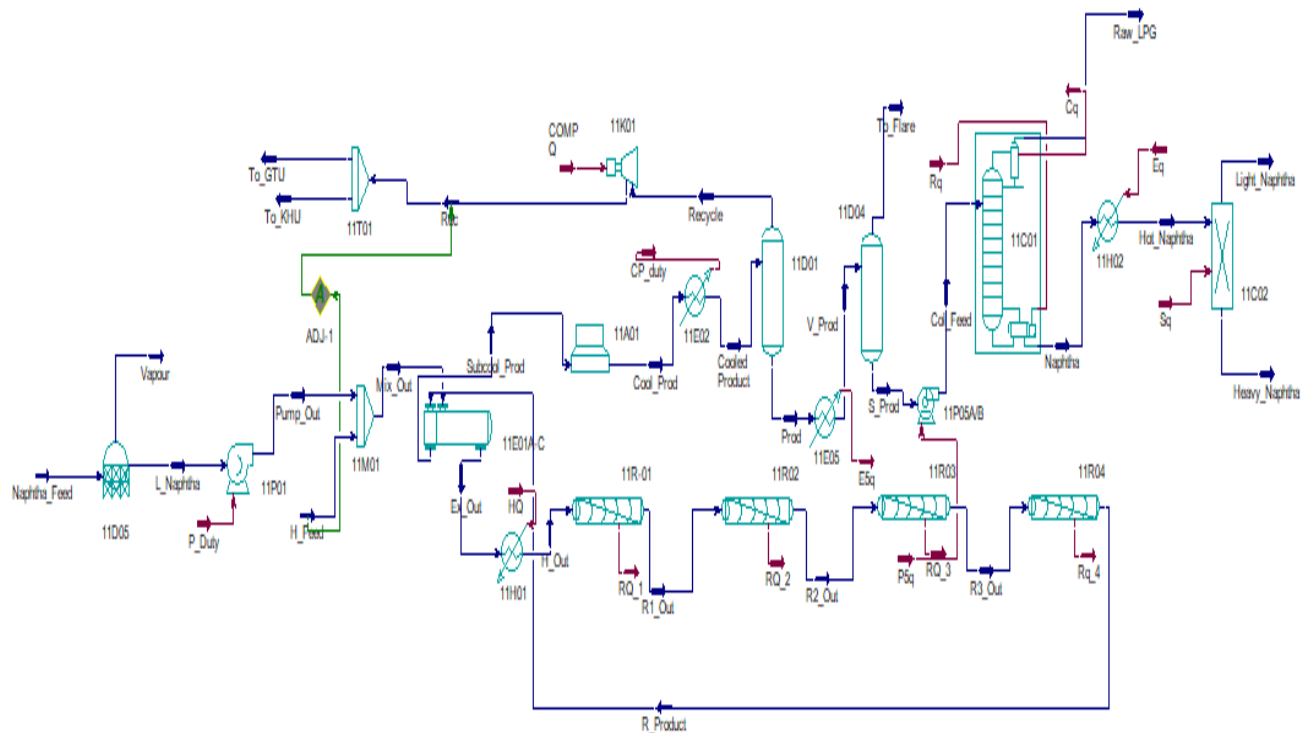


Figure 1: Modeled Naphtha Hydrotreating Unit

3.1 Exergetic efficiency

The result of exergy analysis is shown on Table 1, highlighting the inlet and outlet exergies as well as irreversibility in each equipment. Exergetic efficiency findings shown on Table 2 reveals the Heat Exchanger, Compressor and Plug Flow Reactor have exergetic efficiencies of 51.6%, 64.4% and 84.3% respectively. The low efficiency of the heat exchanger could be due to the fact that almost all of the energy supplied into the unit was dissipated to heat within the process [16]. A very low exergetic efficiency of 23.9% and high value of irreversibility were

found in the Heater 11H01. It was reported that inefficient furnace contributes to the existing problems of environmental pollution and depletion of fossil fuel brought about by higher fuel demand due to a requirement of more energy and higher carbon emission. Inefficiency and heat losses in this unit can be reduced through exploration of process modifications of hot and cold stream temperatures in the Heater and enhancement of heat recovery in the preheat train. The Stripper 11C01 also has a low Exergy efficiency of about 52.8% due to high entropy generation resulting from separation process taking place in the column, these involves momentum loss due to pressure driving force, thermal loss and mass transfer resulting from temperature driving force and mixing of fluids respectively in the column [17].

TABLE 1: RESULT OF EXERGY ANALYSIS

Component	Exergy In (KJ/h)	Exergy Out (KJ/h)	Irreversibility (KJ/h)
Pump 11P01	49703381.00	45378651.00	4324730.00
Heat Exchanger 11E01	36630062.00	18888762.00	17741300.00
Reactor 11R01	2626857.00	2214801.00	412056.00
Heater 11H01	15786896.00	3771457.00	12015438.50
Air Cooler 11A01	24917942.00	15309025.00	9608917.00
Trim Cooler 11E02	33383689.00	24917942.00	8465747.75
Separator 11D01	66459768.00	56661591.00	9798177.28
Trim Cooler 11E05	44062036.00	35153876.00	8908159.50
Separator 11D04	45663764.00	41119391.00	4544373.42
Compressor 11K01	11162030.00	7189484.30	3972545.28
Pump 11P02	56943704.00	55306494.00	1637210.00
Stripper 11C01	55443375.00	29248988.00	26194387.50
Heater 11H02	18195900.00	9101700.00	9094200.00
Splitter 11C02	9101700.00	4433795.80	4667904.20
Total			121385146.00

TABLE 2: EXERGY EFFICIENCY AND CONTRIBUTION TO IRREVERSIBILITY

Component	Exergy Efficiency (%)	Contribution to Irreversibility (%)
Pump 11P01	91.3	3.6
Heat Exchanger 11E01	51.6	14.6
Reactor 11R01	84.3	0.3
Heater 11H01	23.9	9.9
Air Cooler 11A01	61.4	7.9
Trim Cooler 11E02	74.6	7.0
Separator 11D01	85.3	8.1
Trim Cooler 11E05	79.8	7.3
Separator 11D04	90.1	3.7
Compressor 11K01	64.4	3.3
Pump 11P02	97.1	1.3
Stripper 11C01	52.8	21.6
Heater 11H02	50.0	7.5
Splitter 11C02	48.7	3.8
Total		100

3.2 Irreversibility

High irreversibility or destruction of 26194387.5 KJ/hr, 17741300.0 KJ/hr and 12015438.5 KJ/hr were respectively found in the Stripper 11C01, Heat exchanger 11E01 and Heater 11H01, with respective contribution to irreversibility given as 21.6%, 14.6% and 9.9% of the entire lost work as shown on Table 3. This could be as a result of huge losses due to equipment age and inadequate maintenance, however, another reason for high lost work in the stripper column could be due to exergetic losses resulting from entropy generation as a result of temperature variation and pressure drop. Fractionators are known to be associated with low energy efficiency [18]. Exergy losses in the low pressure Separator, Reactor, Compressor and Pumps are quite small, mostly occurring due to resistance and friction losses due to contact with the wall as the fluid flows through the units [19]

3.3 Potential for Revamp

The potential for revamp for each of the components was investigated and the result showed that there are high wastages in energy utilization and high potential for revamp of the Heaters (11H01 and 11H02) and Stripper (11C01) as a result of low efficiencies since they are the major units that determines the overall Exergy efficiency of the Naphtha hydrotreatment process. Heat recovery system (flue gas recovery) in the major contributors to irreversibility is economically viable with a payback period of 3 months in Heater and 7 months in the column [20]. Improvement of boiler system via reduction of energy use by installing Variable Speed Drive (VSD) at the pumps or fans was also explored. Considering information extracted from the process flow diagram and NHU operating manual, tabulated as shown in Table 3, it is recommended that revamp via optimization and design of Heat Exchangers Networks (HENs) should be explored [21].

TABLE 3: STREAM TABLE FOR NHU FROM PFD

Stream Name	Supply Temperature (°C)	Target Temperature (°C)	Heat Duty (kcal/h)
NHU Reactor Feed	39	293	24160000.000
Effluent Exchanger	370	125	24160000.000
NHU Reactor Effluent Trim Cooler	48	40	520000
NHU Reactor Charge Heater	293	370	6380000
NHU LP Separator Charge Cooler	46	40	350000
NHU Stripper Feed	40	133	6410000.000
Bottom Heat Exchanger	237	133	6410000.000
NHU Stripper OH Condenser	77	48	4390000
NHU Stripper OH Trim Condenser	48	40	560000
NHU Stripper Reboiler Heater	200	237	14700000
NHU Splitter Reboiler	114	137	14700000
NHU Splitter Reboiler	221	190	14700000
NHU Splitter OH Condenser	72	55	5090000
NHU Heavy Naphtha Cooler	137	48	2100000
NHU Heavy Naphtha Trim Cooler	48	40	170000
NHU Light Naphtha Cooler	55	35	230000

3.4 Validation of Results

The result of this model was validated by comparing it with plant data as shown in Table 4, a little disparity of 0.0126 in mol fractions were observed, indicating a good agreement between the plant data and model data.

TABLE 4: COMPARISON OF MODEL PREDICTIONS WITH PLANT DATA

Components	This Model (Mol fractions)	Plant Data (Bugaje, 2015)	Difference	% Deviation
M-Naphthenes	0.5494	0.5620	0.0126	-2.2420
H-Naphthenes	0.4506	0.4380	-0.0126	2.8767

4.0 Conclusion

The hydrotreating process that takes place in the NHU of KRPC was successfully simulated using Aspen HYSYS version 8.0. Exergy analysis was carried out and contributions to irreversibility of equipment were estimated to identify major losses. Potential for revamp was explored and heat recovery system was employed and found to be economically viable. Exploration of feasibility of process revamp via energy integration through installation of heat exchanger networks is recommended.

Conflicting Interest: The author declares that there is no conflicting interest.

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