archives
of thermodynamics
Vol. **40**(2019), No. 4, 83–102
DOI: 10.24425/ather.2019.131429

Thermodynamic assessment of crude distillation units: case studies of Nigeria refineries

FUNMILAYO NIHINLOLA OSUOLALE[*a]
AMBROSE NWORA ANOZIE[b]

[a] Department of Chemical Engineering, Ladoke Akintola University of Technology, P. M.B. 4000, Ogbomoso, Nigeria

[b] Department of Chemical Engineering, Covenant University, Km. 10 Idiroko Road, P.M.B. 1023, Canaan Land, Ota, Ogun State, Nigeria

Abstract This paper presents the results of thermodynamic analysis of the crude distillation units of two refineries in Nigeria. The analysis was intended to assess the thermodynamic efficiencies of the refineries and proffer methods of improving the efficiencies. Presented results show the atmospheric distillation units of the refineries have 33.3% and 31.6% exergetic efficiencies and 86.5% and 74.6% energetic efficiencies, respectively. Modifications of the operating and feed conditions of the refineries resulted in increased exergetic efficiencies for as much as 62.3% and 38.7% for the refineries. Thermodynamic analysis of the refineries can bring about efficiency improvement and effectiveness of the refineries.

Keywords: Crude distillation unit; Exergy efficiency; Refineries; Thermodynamic analysis

Nomenclature

a – activity coefficient of component
b – chemical exergy of component, kJ/kmol
Ex – exergy rate, kJ/h
h – specific enthalpy, kJ/kmol

---

[*] Corresponding Author. Email: fnosuolale@lautech.edu.ng

I – irreversibility, kJ/h
m – molar flow, kmol/h
P – system pressure, kPa
R – ideal gas constant, kJ/kmol K
s – specific entropy, kJ/kmol K
T – system temperature, °C

Greek symbols

η – exergy efficiency, %
φ – chemical exergy of pseudocomponent, kJ/kmol

Subscripts

0 – reference conditions
chem – chemical
i – ith component
phy – physical

Abbreviations

ADU – atmospheric distillation unit
HGO – heavy gas oil
LGO – light gas oil
VDU – vacuum distillation unit

1 Introduction

Crude distillation unit (CDU) is significant in the refinery as about 35% of the energy use of the refinery is consumed in the unit [1] and the operating costs of distillation column are often a major part of the total operating cost of the refinery. Developing effective and reliable system for the efficient operation of the crude distillation unit is therefore of paramount importance. Fitzmorris and Mah in 1980 observed that improving the energy efficiency of a distillation column that resulted in 10% energy saving of the column is equivalent to about 100 000 barrels of petroleum per day [2]. This implies that a slight improvement in energy efficiency of the unit can make a large positive difference in profitability. In addition to economic advantage, improved energy efficiency of chemical processes is one of the ways of reducing the greenhouse gas (GNG). Energy generation leads to release of greenhouse gas especially in developing countries like Nigeria that are just coming up industrially leading to environmental pollution and thus defeating the concept of sustainable development [3]. Also, improved efficiency of distillation column will result in a better yield of product and improved product quality. It will also reduce the consumption of energy and thereby lengthen the depleting energy reserve.

To bring about the improvement of the energy efficiency of the crude distillation unit, thermodynamic analysis of the unit is of great relevance. The analysis is based on the second law of thermodynamics rather than the first law and has been applied through exergy analysis and pinch analysis [4]. Exergy analysis is one method of analysis that provides better understanding of a process; quantifies sources of inefficiency [5], distinguishes quality of energy used [6] and allows thermodynamic targets to be defined [7]. Exergy analysis of a distillation column aims at possible reduction in exergy loss. Exergy is a measure of the quality of energy and is the maximum work produced or the minimum required depending on whether the system produces or requires work in bringing the system through reversible process with the environment.

Pinch analysis on the other hand, presents an easy way of incorporating thermodynamics in processes using simple mathematical principle with the resultant effect of optimizing process energy use. It gives the process engineer a clue of optimum energy needed in a process right from the design stage [8], saving efforts and expenses and hence allowing energy targets to be set [9].

While there are many published approaches on determination of exergetic efficiency of crude distillation unit, location and magnitude of exergy loss [10], the strategies to achieve operational improvement is usually uncertain. It is a known fact that operating variables of distillation process have critical effects on product output value and energy consumption. This paper presents the exergy analysis of the crude distillation unit of two refineries in Nigeria with a special emphasis on the operational improvement of the units through process modifications. It is expected that the results of this research will aid the retrofitting of the refineries to bring about the operational efficiency and effectiveness of the refineries. This will go a long way to boost the refineries production process in Nigeria and contribute significantly to the sustainability of the country's economics.

2 Description of the crude distillation units

Two crude distillation units which are functional units of two refineries in Nigeria are considered in this presentation. A diagrammatic representation of crude unit of the first refinery tagged refinery **A** is given in Fig. 1. It is a long column that consists of 46 trays. Three side cuts of kerosene, light gas oil (LGO) and heavy gas oil (HGO) are drawn from the 35th, 26th and 11th trays respectively and processed separately in the strippers. The top pump around (TPA) is taken from tray 44 and sent back to the column above tray 46 by a pump after heat exchange. The intermediate pump around (IPA) is taken from tray 32 and returned to the column above tray 34 by pump after heat exchange. The bottom pump around (BPA) is taken from tray 24 and recycled to the column above tray 25 with the aid of a pump after heat exchange.

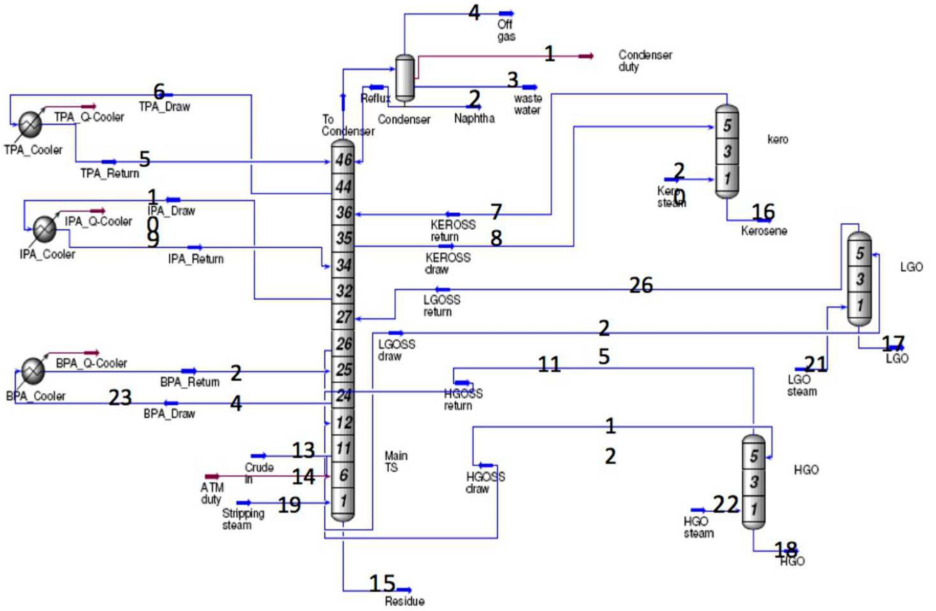

Figure 1: Diagrammatic representation of unit A: TPA, IPA, BPA – bottom, intermediate, top pump around; HGO, LGO – heavy, light gas oil; KERSS, LGOSS, HGOSS – kerosene, LGO, HGO side stripper.

In the crude distillation unit of the second refinery tagged refinery **B**, there are three pumps around on the main column which are denoted as PA1, PA2, and PA3. The first side reflux is drawn from tray 45 and returned to the column on tray 48 after heat exchange, the second is drawn from tray 30 and returned to the column on tray 32 while the third side reflux is drawn from tray 19 and returned to the column on tray 21 after heat exchange. The heavy gas oil was drawn off at the top of tray number 10 and passed into side stripper 3. The light gas oil from tray number 22 passes into stripper SS2 where it is stripped of light end by stripping steam. Kerosene is drawn from tray number 33 and sent to the stripper SS1 where it leaves the light fractions which by effect of the stripping steam return to the column. The overhead product passes to the air fin coolers and then to the overhead accumulator. The unit is represented diagrammatically in Fig. 2.

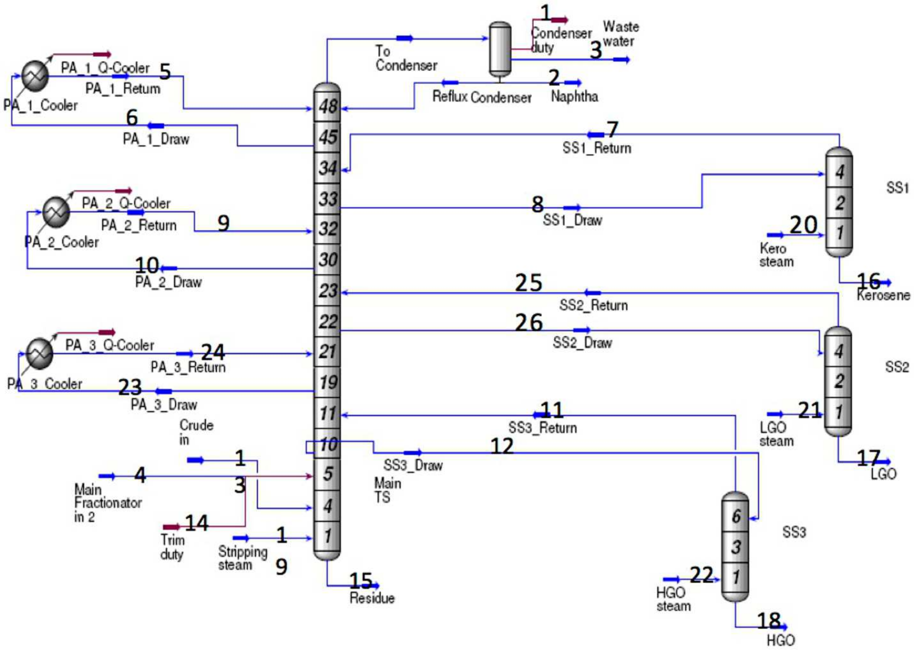

Figure 2: Diagrammatic representation of unit B: HGO, LGO – heavy, light gas oil, PA – pump around, SS – stripper.

2.1 Modeling and simulation of the crude distillation units

The modeling and simulation of the crude distillation units were done in the commercial industry's leading process simulation software Hysys environment [21] using the operating and design parameters of the refineries considered. The property package in Hysys includes equation of states (EOSs), activity models, Chao Seadre models and vapour pressure models. One of the property package in EOS is Peng-Robinson equation. It was chosen as it properly suited crude oil analysis. The light end components of the crude for each of the refineries were determined from the laboratory analysis of the raw crude. Other unknown components of the crude were determined from the crude characterization in Hysys environment. The crude was characterized using experimental assay that include the bulk crude properties, light end volume percent, American Society for Testing and Materials (ASTM) distillation assay, American Petroleum Institute (API) gravity and true boiling point (TBP) distillation assay. The result of the characterization is a set of pseudo-components and a detailed chemical composition of the identified light ends components.

The modeling and simulation of the refineries were done to be prototype of the actual processes as much as possible in terms of their operating and design parameters. These parameters include the number of trays, feed tray, feed temperature, feed flow rates, heat exchangers supply and target temperatures, product specifications, steam flow rates and pump around flow rates. The base case simulation for each of the refinery is the actual operating and design conditions of the refineries.

3 Thermodynamic analysis – exergy analysis

Exergy is a concept from the first and second laws of thermodynamics and its calculation is based on the determination of the enthalpy and entropy of any given system. Usually the physical exergy of a system is calculated as [11]

$$Ex_{ph} = m\left[(h - h_0\ ) - \ T_0\ (s - s_0)\right] \tag{1}$$

with the reference temperature given as 25 °C and the reference pressure as 101.3 kPa. The chemical exergy for some systems such as binary distillation systems may be considered negligible [12] and hence the physical exergy for such systems is taken as the exergy of each stream considered. In this case however, the chemical exergy is calculated as [13,14]

$$\triangle Ex_{chem} = m\Big(\sum \varphi_i + \sum b_i + \mathrm{R}T_0 \sum \ln a_i\Big)\ , \tag{2}$$

where φ_i is the chemical exergy for pseudo-component i , b_i is the chemical exergy for component i, a_i is the activity coefficient of component i. Hence, the total exergy of each stream is an addition of the physical exergy and the chemical exergy of the stream.

Exergy losses in thermal process could be internal loss as a result of irreversible phenomena in the process plant or external loss as a result of waste products from the process. Major losses in the column are considered to be from internal losses. Hence the exergetic efficiency is defined as

$$\eta = \frac{\text{Exergy of useful products}}{\text{Exergy of feed}} = \frac{\sum Ex_{useful\ products}}{\sum Ex_{feeds}}. \tag{3}$$

Subsequently, the irreversibility is calculated as

$$I = \sum Ex_{in} - \sum Ex_{out} , \tag{4}$$

where $\sum Ex_{in}$ is the sum of total exergy into the column and $\sum Ex_{out}$ is the sum of total exergy out of the column.

The overall column efficiency for refinery **A** is defined as

$$\eta_{TA} = \frac{Ex_1 + Ex_2 + Ex_3 + Ex_4 + Ex_{15} + Ex_{16} + Ex_{17} + Ex_{18}}{Ex_{13} + Ex_{14} + Ex_{19}} . \tag{5}$$

The efficiency of the side strippers for refinery **A** were also calculated as:

$$\eta_{s1A} = \frac{E_{x26} + E_{x17}}{E_{x25} + E_{x21}} , \tag{6}$$

$$\eta_{s2A} = \frac{E_{x11} + E_{x18}}{E_{x12} + E_{x22}} , \tag{7}$$

$$\eta_{s3A} = \frac{E_{x7} + E_{x16}}{E_{x8} + E_{x20}} , \tag{8}$$

where η_{s1A}, η_{s2A}, and η_{s3A} are efficiencies for LGO, HGO and kerosene side strippers. The numbers are representing the streams as given in Fig. 1.

Similarly, the total and side strippers efficiencies for refinery **B** are given in Eqs. (9)–(12)

$$\eta_{TB} = \frac{E_{x1} + E_{x2} + E_{x3} + E_{x15} + E_{x16} + E_{x17} + E_{x18}}{E_{x4} + E_{x13} + E_{x14} + E_{x19}} , \tag{9}$$

$$\eta_{s1B} = \frac{E_{x25} + E_{x17}}{E_{x26} + E_{x21}} , \tag{10}$$

$$\eta_{s2B} = \frac{E_{x11} + E_{x18}}{E_{x12} + E_{x22}} , \tag{11}$$

$$eta_{s3B} = \frac{E_{x7} + E_{x16}}{E_{x8} + E_{x20}} . \tag{12}$$

The numbers are representing the streams as given in Fig. 2.

4 Results and discussion

4.1 Exergy and energy analysis

Refinery A Table 1 gives the state parameters for the base case of the simulated atmospheric distillation unit of refinery **A** and the streams that were considered in the thermodynamic analysis. The physical exergy efficiency of the atmospheric distillation unit (ADU) is 33.27% with an irreversibility of 4.2×10^8kJ/h while the total exergy (physical + chemical) efficiency is 33.34%. Here the contribution of the chemical exergy to the efficiency is insignificant (0.17%) and can be considered negligible. The energy efficiency of the column is 86.5%. The result of the simulation gave an exergy efficiency of 90.1% for the preflash with an irreversibility of 3.1×10^7kJ/h. The energy efficiency of the preflash column was 95.9%.

Table 1: State parameters from the simulation for unit A refinery (ADU).

Stream No.	Stream name	Temperature (°C)	Pressure (kPa)	Molar flow (kmol/h)
1	Condenser duty	15.0	–	–
2	Naphtha	184.3	45.00	3387.00
3	Waste water	184.3	45.00	0.00
4	Off gas	184.3	45.00	7106.00
5	TPA return	164.0	50.20	8284.00
6	TPA draw	232.0	50.20	8284.00
7	KEROSS return	258.0	70.48	164.20
8	KEROSS draw	264.1	70.48	2090.00
9	IPA return	207.1	77.40	13730.00
10	IPA draw	275.1	77.40	13730.00
11	HGOSS return	323.5	124.60	90.90
12	HGOSS draw	332.5	124.60	518.40
13	Crude in	350.0	156.90	19140.00
14	Trim Duty	15.0	–	–
15	Residue	324.8	147.10	3455.00
16	Kerosene	243.6	70.48	1962.00
17	LGO	277.3	90.76	3123.00
18	HGO	296.5	103.40	455.70
19	Stripping steam	151.8	500.00	199.80
20	Kero steam	151.8	186.30	36.08
21	LGO Steam	151.8	205.90	83.26
22	HGO steam	151.8	225.60	27.75
23	BPA Draw	308.4	95.27	6233.00
24	BPA return	278.5	95.27	6233.00
25	LGO draw	300.7	90.76	3378.00
26	LGO Return	293.8	90.76	338.6.00

The energy efficiency is higher in both cases than the exergy efficiency because of the non-inclusion of entropy production in its calculation. Every process has an element of irreversibility that makes it to deviate from theoretically ideal possible performance and that is why exergy analysis of a process gives better performance analysis of a process than energy analysis.

Concerted efforts on energy efficiency should be concentrated on the ADU for the overall improvement of the unit.

Refinery B The simulation results for refinery **B** base case are given in Tab. 2 for the ADU and Tab. 3 for the vacuum distillation unit (VDU) showing the inlet streams and the outlet streams. The energy and exergy efficiency as well as the irreversibility were calculated using Eqs. (9)–(12).

Table 2: State parameters for unit B refinery (ADU).

Stream No.	Stream name	Temperature (°C)	Pressure (kPa)	Molar flow (kmol/h)
1	Condenser duty	15.00	–	–
2	Naphtha	48.80	73.55	726.60
3	Waste water	48.80	73.55	815.20
4	Main frac. in 2	144.60	140.00	340.90
5	PA 1 return	50.28	81.67	5142.00
6	PA 1 draw	85.28	81.67	5142.00
7	SS1 return	107.60	94.17	327.50
8	SS1 draw	115.60	94.17	1108.00
9	PA 2 return	89.07	97.29	3282.00
10	PA 2 draw	351.80	97.29	3282.00
11	SS 3 return	197.70	118.10	89.20
12	SS 3 draw	201.00	118.10	465.20
13	Crude in	360.00	2185.00	3688.00
14	Trim duty	15.00	–	–
15	Residue	240.10	127.50	1321.00
16	Kerosene	89.17	94.17	927.00
17	LGO	128.10	105.60	636.90
18	HGO	186.90	118.10	404.10
19	Stripping steam	400.00	4119.00	444.10
20	Kero steam	150.00	343.00	146.25
21	LGO Steam	150.00	343.00	184.00
22	HGO steam	150.00	343.00	28.03
23	PA 3 Draw	179.00	108.70	2745.00
24	PA 3 return	119.00	108.70	2745.00
25	SS 2 return	148.70	105.60	371.40
26	SS 2 draw	159.80	105.60	859.70

Table 3: State parameters for unit B refinery (VDU).

Stream No.	Stream name	Temperature (°C)	Pressure (kPa)	Molar flow (kmol/h)
1	Vacuum tower in	280.0	343.00	1321.000
2	VDU steam	403.0	16.11	135.600
3	LVGO	339.2	13.48	36.300
4	HVGO	376.2	13.91	24.280
5	Vacuum residue	310.0	14.93	2.566
6	Vacuum distillate	279.9	13.33	1212.000
7	Water draw	279.9	13.33	181.700

The total exergy efficiency of the ADU was 31.6% with an irreversibility of 1.3×10^8kJ/h. The contribution of chemical exergy to the total exergy of the main column is 2.2%. The efficiency of the ADU is similar to the results obtained for refinery A. Much of the concentration for improvement of the unit will be on the main column. The energy efficiency of the ADU was found to be 74.6%. This is about 136% increment in the exergy efficiency of the system. The efficiency based on the first law is fictitious and does not adequately give a representation of the column effectiveness as would that based on the second law.

The exergy efficiency of the VDU which was found to be 57.3% further prove the fact that much of the concentration for the improvement of the crude distillation unit should be on the atmospheric distillation unit. The highest irreversibility of 1.3×10^8kJ/h was also found in the ADU while that of the VDU was 6.3×10^7 kJ/h. These deductions and conclusions are in line with the works of Al-Muslim and Dincer (2005) [15] and Cornelissen (1997) [16]. The comparisons table of the efficiencies for refineries **A** and **B** are given in Tab. 4.

Table 4: Comparison of efficiency calculations for unit A and unit B refineries.

Efficiency	Total exergy (%)	Energy (%)	Irreversibility (kJ/h)
Unit A Refinery			
ADU	33.27	86.48	4.17×10^8
Preflash	90.09	95.94	3.12×10^7
Unit B Refinery			
ADU	31.60	74.61	1.308×10^8
VDU	57.26	69.50	6.254×10^7

4.2 Effects of operating conditions

It has been established that concerted efforts for energy efficiency improvement of the crude distillation unit should be concentrated on the main column of the atmospheric distillation unit (ADU) for both refineries. Hence, attention will be paid to the effects that variations of some operating parameters will have on the columns. The choice of parameters here are such that will not affect the existing design by taking into consideration the temperature profile of the columns.

4.2.1 Effects of pump-around flow rate on the thermodynamic efficiency of atmospheric distillation unit

Refinery A The effects of varying the flow rates of the pump around are considered. The initial flow rate of the top pump around, the intermediate pump around and the bottom pump around were 4.49×10^4 barrel/day, 8.05×10^4 barrel/day and 4.024×10^4barrel/day, respectively. A reduction in exergy efficiency was noticed at reduced flow rate while in all the cases considered, exergy efficiency increases with increasing flow rate as depicted in Fig. 3. The essence of the pump-around in a column is to minimize the temperature difference between the hot and cold stream by exchanging heat from the hot stream with the cold stream. This minimises the use of external utilities and hence reduces the cost of production. Also withdrawing a hot stream and returning it back to the column at a reduced temperature conserves heat within the column and reduces the amount of high content heat released from the column leading to reduction in the heat requirement of the overhead reflux [17]. This explains the reason why increasing flow rates of the pump-around increases the exergy efficiency. However, the energy efficiency decreases with increasing pump-around flow. This might be due to the fact that energy efficiency is calculated irrespective of temperature difference between the inlet and outlet streams. It is based on the quantity of energy and not the quality on which exergy analysis was based.

As expected, the irreversibility for all the considered cases is reduced with increasing flow rate. This is showing a thermodynamic improvement on the operating conditions and further attesting to the fact that major causes of inefficiency in a column is due to production of irreversibility. When the irreversibility of a system decreases implying a reduction in entropy generation of the system, efficiency of the column increases as well. It should however be noted that increase in the column exergetic efficiency is relatively small for all the pump around considered, from initial value of 33.27% to final values of 33.59%, 33.53% and 33.37% for the top pump around (TPA), intermediate pump around (IPA) and bottom pump around (BPA), respectively. The advantage of increasing the flow rate of the pump around which leads to a more energy efficient column should be weighed with the capital cost implications before being utilized.

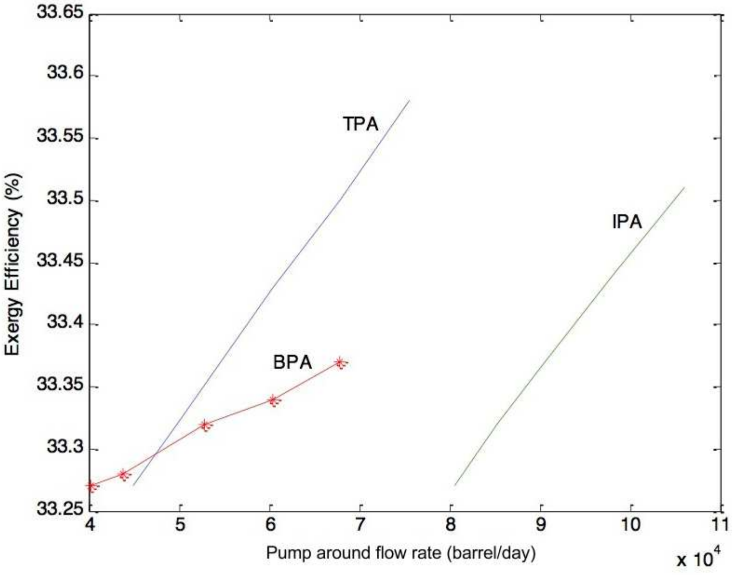

Figure 3: Variation of pump around flow rate wirh exergy efficiency for refinery **A**.

Refinery B There are three pumps arounds in unit **B** refinery. The effects of varying pump around flow rate on the thermodynamic efficiency of the column are graphically depicted in Fig. 4. The flow rates of the pump arounds are directly proportional to their exergy efficiencies. This follows the trend of refinery **A**. A more drastic step may be needed to increase the efficiency if the cost of running the column at this increased flow rate is not commensurate with the accrued column efficiency. It has however been established that increase in the pump around rate increases the column efficiency.

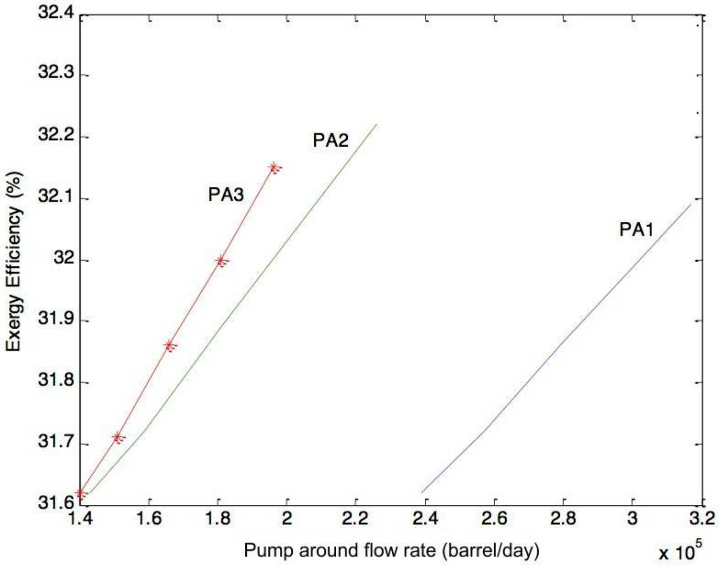

Figure 4: Variation of pump around flow rate wirh exergy efficiency for refinery **B**.

4.2.2 Effects of pump around temperature drop

The effects of pump around temperature variations on exergy efficiency, energy efficiency and irreversibility is similar to that of the pump around flow rate variations. The effects follow the same trend for the two refineries and are depicted graphically in Figs. 5 and 6.

Figure 5 shows the effects of pump around temperature on the thermodynamic efficiency of the crude distillation unit of refinery **A**. Exergy efficiency was increasing directly with the temperature drop. Pump around temperature drop is meant to control the column temperature. An increase in the temperature drop brings about a corresponding increase in the efficiency of the column. This is because much of the heat energy carried in the pump around is integrated into other parts of the column where heating utility could have been used. An increase in the temperature drop implies that the flow is returned at a lower temperature that brings about a reduction in condenser duty and hence makes the column to operate more efficiently. The energy efficiency decreases with increasing pump around temperature drop. This arises because of the seemingly rise in energy usage in the column but in actual fact, the quality of the energy used is improved, what could have been dissipated as waste is being put to use in the column. There is no further addition of energy showing that first law analysis gives a fictitious energy efficiency of processes. It is pertinent to note that operating the column at an increased pump around temperature makes the column more exergy efficient. The best operating temperature drop will however depend on some other design considerations but in cases where it is allowed to go up, it is economical in terms of exergy to do so.

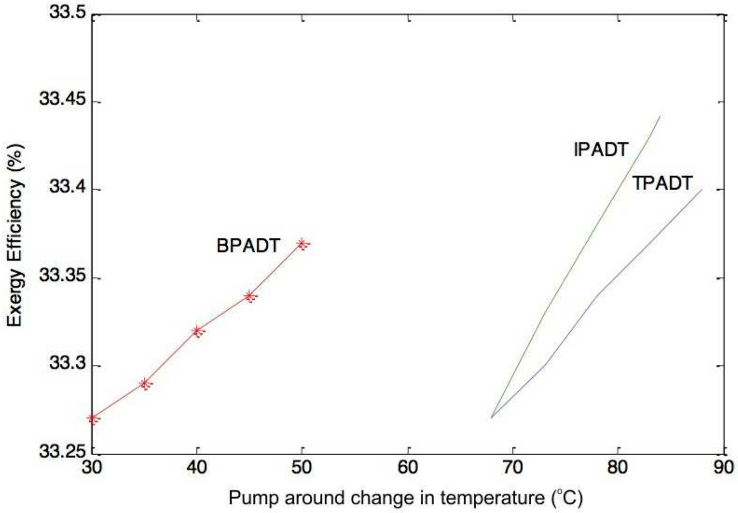

Figure 5: Effects of pump around temperature on exergy efficiency of refinery **A**.

Figures 6 give the effects of pump around temperature drop on the exergy efficiency of refinery **B**. The exergy efficiency is directly proportional to the temperature drop as it was for refinery **A** for each of the pump around temperature drop. In each case, increase in exergy efficiency was less than 1%.

The usual trend was also applicable here for the ADU energy efficiency, varying inversely with the temperature drop.

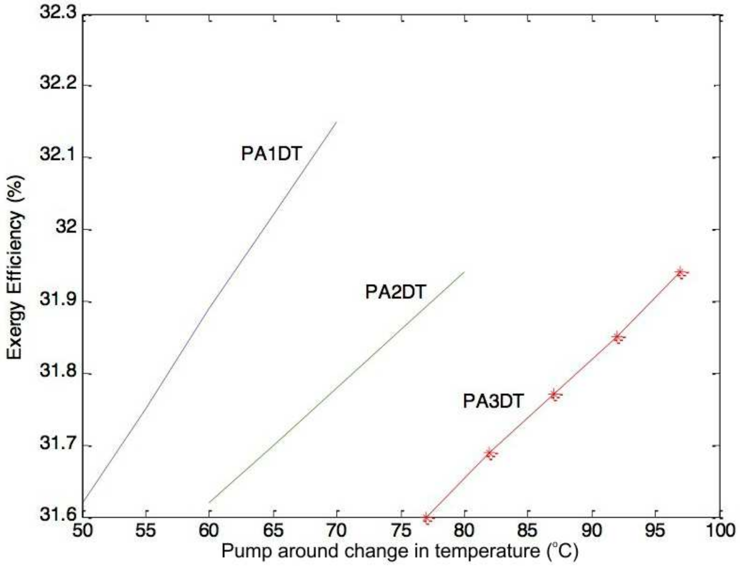

Figure 6: Effects of pump around temperature on exergy efficiency of renifery **B**.

4.3 Effects of feed conditions

The effects of some selected feed conditions on the exergy and energy efficiency of the column are considered in this section. Feed to a distillation column usually comes from another column or other unit operations. Therefore, knowing the effects of thermal condition of the feed on the thermodynamic performance of the column and hence the overall performance of the process will aid in improving the thermal condition of the feed right from the preceding unit operation with the overall effect of optimum performance of the column.

4.3.1 Effects of feed temperature

The effects of the feed temperature on the thermodynamic efficiency of the column are shown in Fig. 7 for the two refineries. The thermodynamic efficiency of refinery **A** increased from 33.3% to 54% for a reduction in feed temperature from 360 °C to 300 °C. The main cause of irreversibility in a column is as a result of temperature driving force at the reboiler as well as condenser. Therefore the energy efficient design of the reboiler as well as the condenser is paramount for an efficient column. The irreversibility of the column reduced from 4.52×10^8 kJ/h to 1.75×10^8 kJ/h for refinery A; this considerable decrease in the irreversibility with a corresponding increase in the column efficiency suggests the feed temperature as one of the best stand-alone condition of column improvement. Sea *et al.* (2000) has pointed out that one of the major indices of a correct column operation is the temperature profile which can be brought about by the feed parameters [17]. A careful selection of the temperature inlet of the feed is therefore important for an optimum distillation column operation.

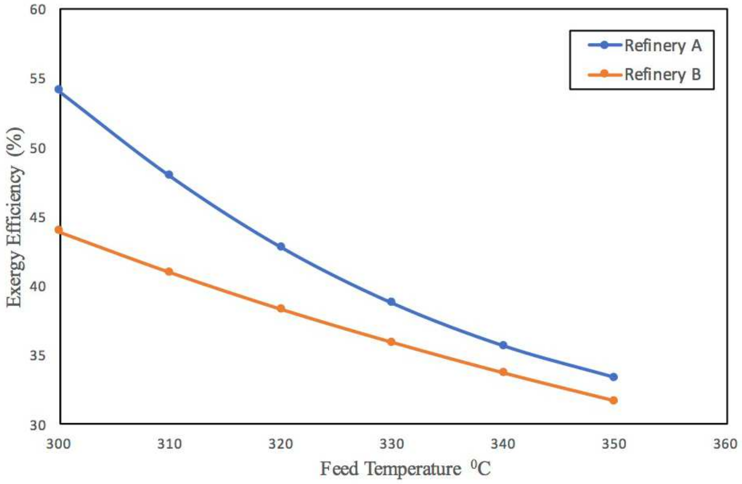

Figure 7: Effects of feed temperature on exergy efficiency of the crude distillation unit.

The extent of increase in efficiency in refinery B is though not as appreciable as that of refinery **A** and is ranging from 31.6% to 43.9% for the same temperature range as refinery **A**. The thermal condition of the feed is also influenced by the feed compositions [18]; this may be the reason for the disparity in change in efficiency for the refineries at the same feed temperature ranges. It has however been confirmed that feed conditions play an important role in the thermodynamic efficiency of the column.

The energy efficiencies of the ADU and VDU is constant over the range of temperatures considered showing that the feed temperature has no effect on the energy efficiency of the column. However, the VDU exergy efficiency as well as the ADU exergy efficiency increases with a reduction in the feed temperature. There is a limit to which this reduction can be made as the crude is meant to be introduced to the column at its flash point. For the refineries considered, the feed temperature could be adjusted to improve the efficiency of the columns.

A reduction in irreversibility of the column from 1.30×10^8 kJ/h to 7.10×10^7 kJ/h was noticed for the temperature range of 360 °C to 300 °C. The increase in the column efficiency with a corresponding reduction in column's irreversibility shows the need to pay great attention to the condition of the feed in order to have an efficient column.

4.3.2 Effects of feed ratio

Feed to crude distillation column is usually preheated by the high heat content products from the sides and bottom of the column and an external heat supply. The outcome of possibly splitting the feed stream into two and heating only one of the streams with the external heat supply on the thermodynamic efficiency of the column is the major concern here. Half of the feed was bypassed by the heater and fed to the upper part of the column tray 40 for unit **A** refinery and tray 30 for unit **B** refinery. The trays were chosen in such a way that the reference column efficiency was not compromised.

An increase in exergy efficiency to 73.9% and 61.4% was noted for unit **A** and **B**, respectively. The energy demand of the reboiled steam has been reduced and so was the energy of the condenser as a result of the introduction of the 'cold feed' at higher tray level. The capacity of the tower was also increased as the vapor and liquid traffic along the tower is decreased. These observations are consistent to that of Soave and Feliu [19].

The energy efficiency of the ADU deviates from the usual trend of decreasing while exergy efficiency was increasing; rather it was increasing with increasing exergy efficiency. The irreversibility of the columns followed the expected trend of reducing with increasing efficiency. Refinery **A** reduced from 4.18×10^8 kJ/h to 7.57×10^7 kJ/h while refinery **B** reduced from 1.30×10^8 kJ/h to 3.63×10^7 kJ/h.

4.3.3 Effects of feed pressure

Figure 8 gives the effects of the feed pressure on the column efficiency using unit refinery **A** as case study. Column efficiency is often reduced as a result of pressure drop in the column and hence, for a given thermal condition and feed composition, the efficiency of the column can be increased by changing the operating pressure. This fact is further iterated in Fig. 8 with increase in column's efficiency as the column feed pressure increases. This is because higher operating pressure leads to lower entropy generation as a result of lower pressure drop within the column and hence the need for the design of better tray internals for lower pressure drop for an efficient column. Bandyopadhyay gave a similar conclusion [20].

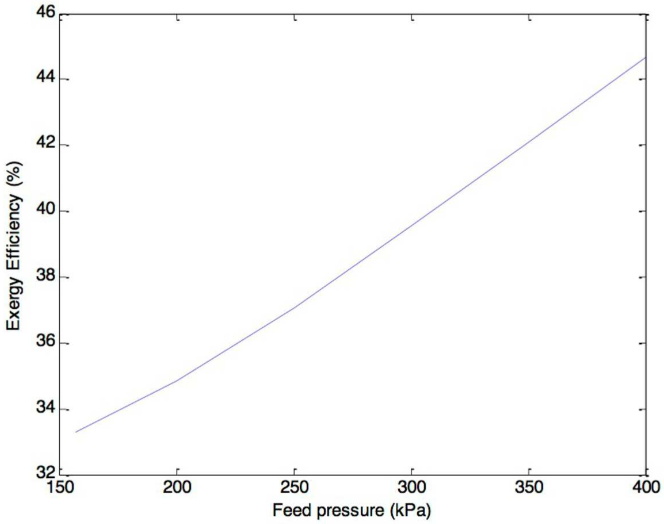

Figure 8: Effects of feed pressure on exergy efficiency of renifery **A**.

5 Conclusions

The thermodynamic efficiency of the crude distillation column is the sole criterion in considering the feed and the operating conditions of the refineries analysed in this study. In practice however, some other conditions such as operating and capital costs, operational complexity and flexibility would have to be considered to determine the best design and operating conditions. Thermodynamic analysis of the column however gives an in-depth and useful understanding of the column. Based on the exergy analysis of the refineries, the following can be concluded:

1. The crude distillation units of both refineries considered are grossly inefficient in terms of the second law analysis. The atmospheric distillation unit in both cases contributes mostly to the source of inefficiency of the systems. Refinery **A** is 33.3% exergetically efficient while unit **B** refinery is 31.6% efficient.

2. The operating parameters of the column such as pump around flowrate, pump around change in temperature and feed conditions have effects on the performance of the column and should be carefully chosen. From the presented analysis, pump around flow rate and temperature drop could bring about 1–2% improvement in the exergy efficiency of the crude distillation units of the refineries. Change in the operating feed temperatures of the refineries could bring about 62% improvement for crude distillation unit of refinery **A** and about 38.7% for crude distillation unit of refinery **B**. Feed ratio increase the exergy efficiency of the atmospheric distillation unit of refinery **A** from 33.3% to 73.9% and that of refinery **B** from 31.6 to 61.4%.

Present operating conditions of the columns and the feed conditions of the two refineries are not at optimum values and hence should be corrected for effective operation of the columns. The improvements come not only from heat recovery projects, but also from changing process conditions, improved operability and more effective interfacing with utility systems, all underpinned by better process understanding through the second law analysis.

Acknowledgement The authors appreciate the support provided by the studied refineries and the Obafemi Awolowo University, Ile-Ife, Nigeria.

Received 10 December 2018

References

[1] Sankaranarayanan K., Arons J.D.S., Kooi, H.J.V.D.: *Efficiency and Sustainability in the Energy and Chemical Industries.* CRC Press, Taylor and Francis, 2010.

[2] Fitzmorris R.E., Mah R.: *Improving distillation column design using thermodynamic availability analysis.* AICHE J. **6**(1980), 2, 265–273.

[3] Dincer I.: *Energy and environmental impacts: present and future perspectives.* Energ. Sources **20**(1998), 427–453.

[4] Stanek W., Budnik M.: *Application of exergy analysis for evaluation of CO_2 emission from operation of steam power unit.* Arch. Thermodyn. **31**(2010), 4, 81–91.

[5] Sekret R., Nitkiewicz A.: *Exergy analysis of the performance of low-temperature district heating system with geothermal heat pump.* Arch. Thermodyn. **35**(2014), 1, 77–86.

[6] Budnik M., Stanek W.: *Exergetic cost of a steam power plant operation.* Arch. Thermodyn. **32**(2011), 2, 39–54.

[7] Dudar A., Butrymowicz D., Śmierciew K., Karwacki J.: *Exergy analysis of operation of two-phase ejector in compression refrigeration systems.* Arch. Thermodyn. **34**(2013), 4, 107–122.

[8] |sc Linnhoff B., Hindmarsh E.: *The pinch design method of heat exchanger networks.* Chem. Eng. Sci. **38**(1983), 5, 745–760.

[9] Linnhoff B., Dunford H., Smith R.: *Heat integration of distillation column into overall processes.* Chem. Eng. Sci. **38**(1983), 8, 1175–1188.

[10] Dincer I., Rosen M.A.: *Exergy:energy, environment and sustainable development.* Elsevier , Oxford 2012.

[11] Anozie A.N., Osuolale F.N., Aseeperi T.C.: *Exergy analysis and optimization of binary plate distillation column operations.* Int. J. Exergy **7**(2010), 5, 593–606.

[12] Anozie A.N, Osuolale F.N., Osunleke A.S.: *Exergy analysis of binary plate distillation column operations.* Int. J. Exergy **6**(2009), 5, 715–728.

[13] Szargut J., Morris D.R., Steward F.R.: *Exergy Analysis of Thermal, Chemical and Metallurgical Processes.* Hemisphere, New York 1988.

[14] Rivero R., Rendón C., Monroy L.: *The exergy of crude oil mixtures and petroleum fractions: calculation and application.* Int. J. Appl. Thermodyn. **2**(1999), 3, 115–123.

[15] Al-Muslim H., Dincer I.: *Thermodynamic analysis of crude oil distillation Systems.* Int. J. Energy Res. **29**(2005), 637–653.

[16] Cornelissen R.L.: *Thermodynamics and sustainable development, the use of exergy analysis and the reduction of irreversibility.* PhD thesis, University of Twente, Enschede 1997, http://www.ub.utwente.nl.webdocs/wb/1/t0000003.pdf (assesed 5 March 2007).

[17] Sea J.W., Oh M., Lee T.H.: *Design optimization of a crude oil distillation.* Chem. Eng. Technol. **23**(2000), 2, 157–164.

[18] Agrawal R., Herron D.M.: *Optimal thermodynamic feed conditions for distillation of ideal binary mixtures.* AIChE J., **43**(1997), 11, 2984–2996.

[19] Soave G., Feliu J.A.: *Saving energy in distillation towers by feed splitting.* Appl. Therm. Eng. **22**(2002), 889–896.

[20] Bandyopadhyay S.: *Effect of feed on optimal thermodynamic performance of a distillation column.* Chem. Eng. J. **88**(2002), 1-3, 175–186.

[21] HYSYS (2003) Version 3.2 (Build 5029), aspen Technology Inc., Licensed to TEAM LND, Calgary, Alberta, Canada