Full Paper

THERMODYNAMIC ANALYSIS OF A CRUDE OIL DISTILLATION UNIT

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ABSTRACT

Crude distillation unit is an essential part of the crude oil refinery system and it is an energy intensive process. This work presents a thermodynamic analysis of the unit with the aim of improving its efficiency. HYSYS was used in simulating the crude distillation unit at its operating conditions. The overall efficiency was found to be 31.98%. Exergy loss profile and exergy rate diagram on a tray by tray level were used in assessing the column for regions of high entropy generation. The result shows the feed tray to be a region of high exergy loss. Modification of the feed conditions will therefore improve the efficiency of the column.

Key Words: *Thermodynamic analysis, exergy loss, exergy rate, efficiency.*

1. INTRODUCTION

The thermodynamic analysis is based on the first and second laws of thermodynamics rather than the first law alone and has been applied through pinch analysis, equipartition principle and exergy analysis [1]. Thermodynamic analysis of a distillation column is important for developing an energy efficient column [2]. Crude oil distillation column is one of the most energy consuming process and one of the least energy efficient processes. This is because of the heat transfer with large temperature driving force, mass transfer between the liquid, vapour state and pressure drops along the column. Thermodynamic analysis of a distillation column therefore aims at identifying and possibly quantifying regions of inefficiency within the column and setting up thermodynamic targets for further improvements [3-6].

Exergy analysis 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 [7-9]. Exergy analysis gives an indication of how efficient a system is in relation to the theoretically possible efficiency of the system. Exergy being a measure of the quality of energy allows costing of the utilized energy in every part of the production route in any given process [10]. Detection of inefficient processes in terms of energy and cost allocation makes room for development of efficient process which will lengthen reserves of existing energy sources and allows for optimum usage of material, thereby ultimately leading to sustainable development.

Exergy analysis of a stream of matter is made up of four different components of exergy; the physical exergy, chemical exergy, kinetic exergy and potential exergy [11]. Physical exergy is the work obtainable by taking the substance reversibly from an initial temperature and pressure to the reference temperature and pressure of the environment. Chemical exergy is the work obtainable by taking the substance in chemical equilibrium with the reference level components of the environment. Kinetic exergy is the exergy when the velocity of a stream is considered relative to the surface of the earth while potential exergy is evaluated with respect to the average level of the earth surface.

2. PROCESS DESCRIPTION

Crude oil is usually processed in two stages in most distillation plants. The first is the atmospheric distillation column (ADU) for light fractions and the second is the vacuum distillation column (VDU) for heavier fractions. The products from each column may serve as the feed to another processing plant or may be the final product. This study is basically on the ADU. Crude oil processing facilities consists of pre-flash train used to heat the crude column to fractionate the crude into its straight product. Having passed through desalination and cleaning processes, preheat crude is fed to the preflash-drum where vapour is separated from the crude liquid. The overhead vapours are condensed in the preflash overhead receiver from which the stream is separated into off gas, light naphtha and condensed water. The preflash bottom liquid is then heated in the crude furnace. The crude charge from the furnace, partly liquid and partly vapour is introduced into the flash zone of the atmospheric distillation column (ADU). The ADU operates above atmospheric pressure. It is a long column that consists of 46 trays. The liquid drawn from the bottom tray is called the atmospheric residue. The overhead vapours are condensed in the atmospheric column air cooler and collected in accumulator. The top pump around (TPA) is taken from tray 44 and sent back to the column above tray 46 by 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 pump after heat exchange.

Both column bottom liquid and the liquid side cuts contain light ends. Light ends removal is achieved by injecting steam. The three side cuts are drawn respectively from the 35th, 26th and 11th tray and processed separately in the strippers. The kerosene cut is fed into the kerosene stripper, above the 5th trays and vapours return to main column above the 36th tray, while the stripped kerosene is sucked from bottom by pump and sent to storage. The LGO cut is fed into the LGO stripper above the 5th tray and vapours return to main column above the 27th tray. The HGO cut is fed into the HGO stripper above the 5th tray and vapours return to main column above the 12th tray while the stripped HGO is sent to storage. The schematic diagram of part of crude oil distillation plant is shown in Figure1.

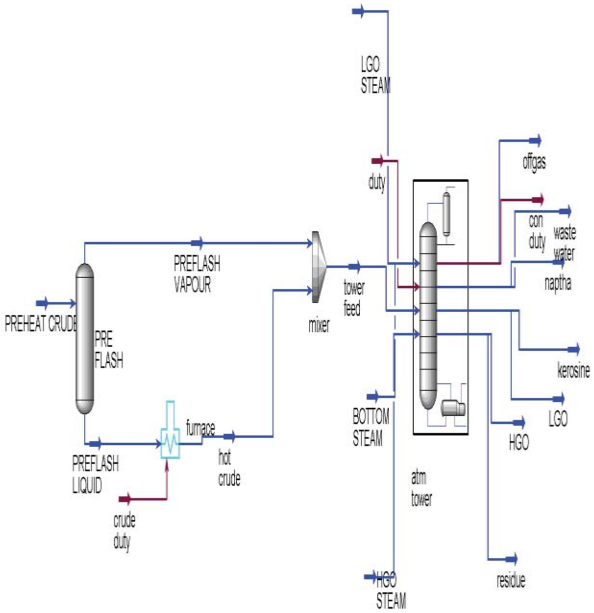

Figure 1: Schematic diagram of crude distillation unit

3. THE SIMULATION

Crude oil is a mixture of identified components and unidentified components called pseudo-components. The crude was characterised using experimental assay that include the bulk crude properties, light end volume percent, ASTM distillation, API gravity and TBP distillation. The assay data was fed into the data bank of the simulator software (HYSYS). The result of the characterisation is a set of pseudo-components (37 in number) and a detailed chemical composition of the identified light ends components. There are different property package options set available in HYSYS. Peng Robinson which is well suited for petroleum fractions was used in this case. The modelling of the column was done in the HYSYS environment at the operating parameters of the column. The column comprises of 46 trays with three side strippers and three pump around. Data such as entropy, enthalpy, temperatures, pressures, compositions and stream flow rates were extracted from the simulation for analysis

3.1. Method of Analysis

The physical and chemical exergies are considered as follows:

$$\Delta Ex = \Delta Ex_{phy} + \Delta Ex_{chem} \qquad (1)$$

$$\Delta Ex_{phy} = \Delta H - T_0 \Delta S \qquad (2)$$

The physical exergy comprises of the pressure and temperature parts

$$Ex_{phy} = (T - T_0) - {T_0 \ln T}/{T_0} + {RT_0 \ln P}/{P_0} \qquad (3)$$

The chemical exergy is given by [11,12]

$$\Delta Ex_{chem} = \sum \varphi_i C_i + \sum n_i b_{chi} R T_0 \sum n_i ln a_i \qquad (4)$$

b_{chi} is the chemical exergy for component i

a_i is the activity coefficient of component i

φ_i is the regression equation determined to express the ratio H/C, N/C, O/C and S/C for the hypocomponents.

C_i is the net calorific heating value of the pseudocomponent i.

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

$$\eta = \frac{\text{Exergy of useful products}}{\text{Exergy of feed}} \qquad (5)$$

For the overall column the efficiency is defined as

$$\eta_T = \frac{Ex_1 + Ex_2 + Ex_{15} + Ex_{16} + Ex_{17} + Ex_{18}}{Ex_{13} + Ex_{14} + Ex_{19}} \qquad (6)$$

The efficiency of the side strippers were also calculated as

$$\eta_{s1} = \frac{Ex_{26} + Ex_{17}}{Ex_{25} + Ex_{21}} \qquad (7)$$

$$\eta_{s2} = \frac{Ex_{11} + Ex_{18}}{Ex_{12} + Ex_{22}} \qquad (8)$$

$$\eta_{s3} = \frac{Ex_7 + Ex_{16}}{Ex_8 + Ex_{20}} \qquad (9)$$

Where η_{s1} , η_{s2} ,and η_{s3} are efficiencies for LGO, HGO and Kero side strippers, respectively.

3.2. Exergy loss profile

The exergy loss profile describes in a single variable the exergy losses in the column. It represents a loss due to the existence of driving forces within the column. It is given for each tray of the column as

$$Ex_{tray} = (Ex_{in}^{vap} + Ex_{in}^{liq} + Ex_{in}^{feed}) - (Ex_{out}^{vap} + Ex_{out}^{liq} + Ex_{side}) + Q\left(1 - \frac{T_o}{T_{heat}}\right) \qquad (10)$$

3.3. Exergy Rate Diagram

The exergy rate diagram shows the distribution of driving forces within the column between the liquid and the vapour state of each tray. It equally shows the feasibility of the column design. A crossing of the graphs is thermodynamically infeasible and connotes an infeasible design [13, 14]. It is calculated for the liquid and vapour state of each tray as

$$\Delta Ex_{tray} = \Delta H - T_0 \Delta S \qquad (11)$$

4. RESULTS AND DISCUSSION

The results from the simulation are tabulated in Table 1. The state properties obtained for each of the streams are used in the calculation of exergy. The overall efficiency of the column is 31.98%. The efficiency of the side strippers are 67.8%, 97.2% and 58.6% for the LGO, HGO and Kero side strippers, respectively. The low overall efficiency is an indication of high entropy generation or exergy loss within the column.

The exergy loss profile is shown in Figure 2. The loss is negligible in many trays but very high in the sixth tray which is the feed tray and fairly high in the last tray. Improving the operating conditions in the feed tray will have a significant increase on the overall efficiency of the column.

The exergy rate diagram for the column is plotted in Figure 3. This shows the distribution of the driving forces along the column. The increase in the difference in the liquid and vapour exergy rate is noted from the sixth tray upward. This is also attesting to the fact that concentration on improving the sixth tray will have a positive overall effect on the efficiency of the column. However, exergy rate diagram gives deeper insights into the happenings in the column. The difference in driving forces is only small above the feed tray, it is very high in the feed tray and after decreases but still appreciable in the remainder of the column. The exergy diagram shows more regions of exergy losses than the exergy loss profile. The kinks on the 11th, 26th and 35th trays where the side cuts were drawn indicate regions of increase or reduction in driving forces within the column and hence pointing to areas that could be improved upon for ultimate increase of the column's efficiency.

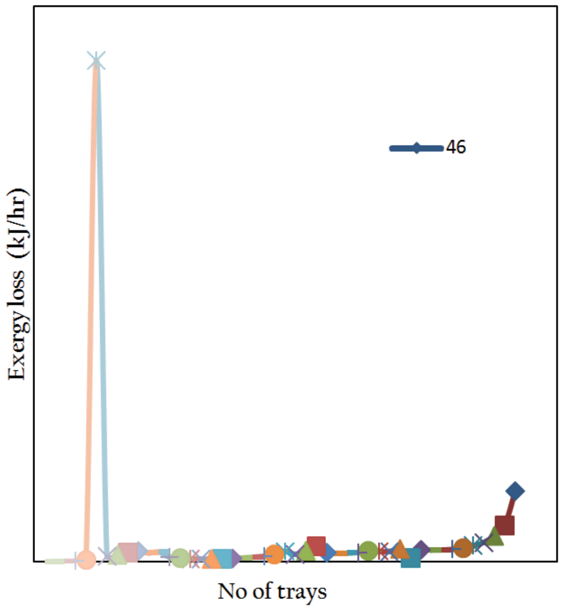

Figure 2: Exergy loss profile

Table 1: State parameters from the simulation

S/N	Type	T(^{0}C)	P (kPa)	Molar Flow(kg/hr)	H(kJ/kg)	S(kJ/kgK)	Ho (kJ/kg)	So (kJ/kgK)	B(kJ/kg)
1	Condenser	15							-1.273e8
2	Distillate	137.8	14.7	4.094e4	-2.083e5	183.8	-2.588e5	31.2	2.074e8
3	Waste water	137.8	14.7	3570	-1.230e5	-65.55	-1.381e5	-107.2	9.334e6
4	Vapour production	137.8	14.7	0.000	-1.230e5	-65.55	-1.381e5	-107.2	0.0000
5	TPA return	185	25.38	7993	-1.284e5	-61.82	-1.521e5	-124.7	3.952e7
6	TPA draw	253	25.38	7993	-1.167e5	-37.95	-1.521e5	-124.7	7.650e7
7	KERO return	272.2	73.43	5372	-2.073e5	185.7	-2.643e5	22.59	4.499e7
8	KERO draw	325.8	73.43	3312	-1.140e5	-11.89	-1.679e5	-134.6	5.7759e7
9	IPA return	306.8	89.45	1.338e4	-1.239e5	-19.55	-1.753e5	-139.8	2.079e8
10	IPA draw	351.8	89.45	1.338e4	-1.144e5	-3.751	-1.753e5	-139.8	2.723e8
11	HGO return	472.8	201.6	3605	-1.808e5	191.8	-2.710e5	1.077	1.203e8
12	HGOdraw	521.8	201.6	2771	-1.143e5	62.72	-2.415e5	-183.3	1.493e8
13	Feed in	350	225.6	1.796e4	-9e4	39.68	-1.613e5	-112.3	4.606e8
14	Trim Duty	15							-1.177e8
15	Residue	348.3	255.0	448.1	-2.199e5	-20.76	-3.182e5	-243.4	1.430e7
16	Kerosine	195.5	73.43	2585	-1.407e5	-59.62	-1.709e5	-136.4	1.887e7
17	LGO	180.7	121.5	2583	-1.696e5	-74.75	-2.011e5	-158.2	1.716e7
18	HGO	359.4	201.6	1941	-1.659e5	-2.012	-2.496e5	-188.2	5.462e7
19	Bottom steam	358.6	1442	1.253e4	-2.298e5	177.3	-2.854e5	53.70	2.357e8
20	Kero steam	151.8	205	4645	-2.368e5	179.7	2.854e5	53.70	5.136e7
21	LGO steam	151.8	205.9	1.443e4	-2.368e5	179.7	2.854e5	53.70	1.597e8
22	HGO steam	151.8	205	2775	-2.368e5	179.7	2.854e5	53.70	3.069e7
23	BPA Draw	438.1	132.2	6129	-1.152e5	25.09	-2.051e5	-162.1	2.092e8
24	BPA return	408.1	132.2	6129	-1.228e5	14.05	-2.051e5	-162.1	1.823e8
25	LGO draw	413.5	121.5	3411	-1.146e5	17.97	-1.956e5	-153.9	1.017e8
26	LGO Return	314.9	121.5	1.526e4	-2.209e5	192.4	-2.774e5	37.85	1.603e8

Table 2: Efficiency Calculations

	Column efficiency (%)	LGO side stripper efficiency (%)	HGO side stripper efficiency (%)	KERO side stripper efficiency (%)
Base case	31.98	67.8	97.2	58.6
At 300^{0}C Feed Rate	46.8	67.8	97.2	58.6

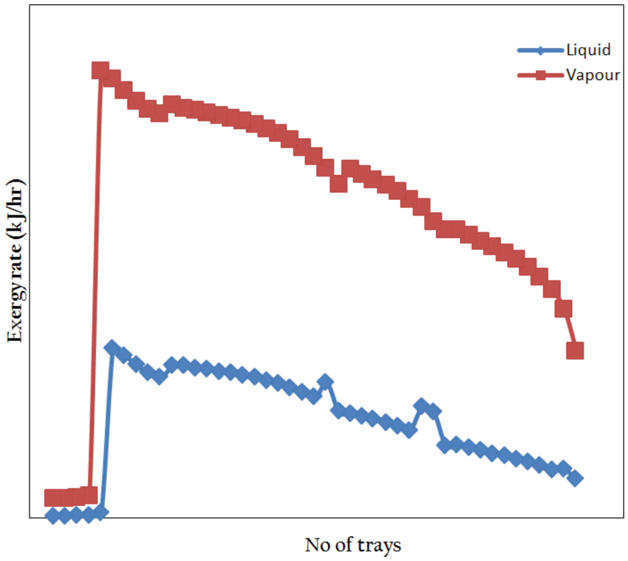

Figure 3: Exergy rate diagram

A reduction in the feed temperature from 350°C to 300°C gave overall exergy efficiencies of 46.8%, 67.8%, 97.2% and 58.6% for the column, LGO, HGO and Kero side strippers, respectively. The exergy loss profile and the exergy rate diagram for the feed temperature of 300°C are shown in Figures 4 and 5, respectively. No significant variations were observed in the two profiles indicating that the change in feed temperature did not impact the operation of the column significantly. However, the efficiency values indicated that it is better to operate the column at 300°C.

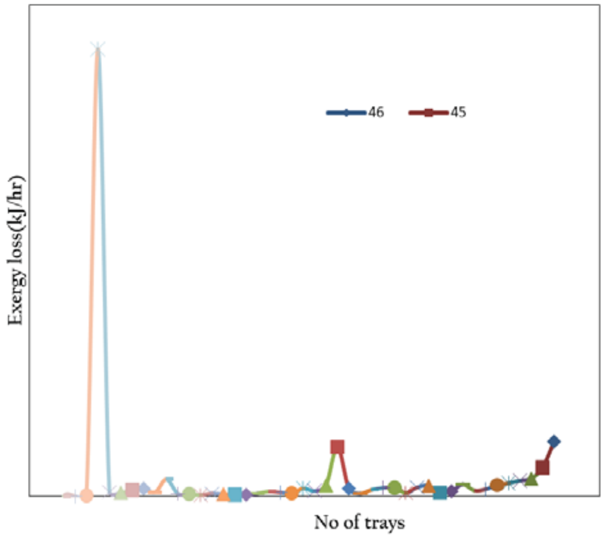

Figure 4: Exergy loss profile at 300^{0}C feed temperature

Exergy analysis is a function of the state parameters as well as the reference state. This is further complemented in Figure 6 for a variation in reference state from 288K to 328K. An increase in efficiency is noted for a reduction in reference temperature. Exergy is the work required or produced in bringing a system to thermal equilibrium with the environment. The closer a system is to the environment states, the higher the efficiency is likely to be. A careful consideration of the environmental state is therefore needed in the second law analysis of the system.

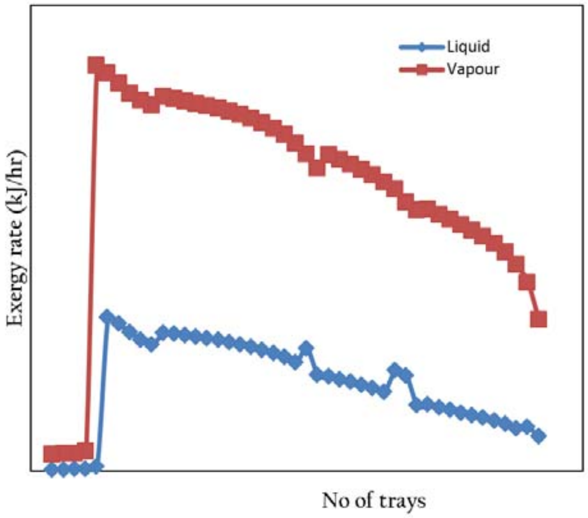

Figure 5: Exergy rate diagram at a feed temperature of 300^{0}C

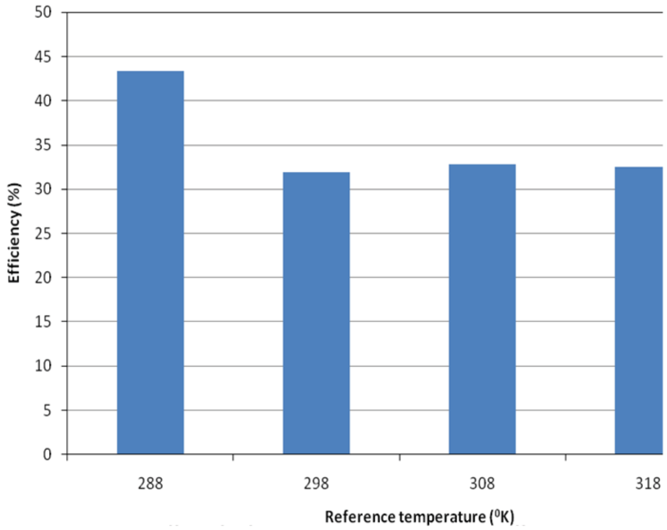

Figure 6: Effect of reference temperature on exergy efficiency

5. CONCLUSIONS

This paper has successfully presented the second law analysis of a crude distillation unit. The low efficiency of the process suggests a serious need for improvement. Exergy loss and exergy rate diagram graphically depict regions of high inefficiency or entropy generation in the system. Exergy rate diagram gives better insights to the thermodynamics activity within the column and is therefore a preferable methodology for column improvements. The reference states of the environment play a significant role in the thermodynamic analysis of a process.

REFERENCES

[1] Y. Demirel, Retrofit of distillation columns using thermodynamic analysis, *Separation Sciences and Technology*, *41*,2006, 791–817.

[2] M. Gadalla, M. Jobson and R. Smith, Optimization of Existing Heat-integrated Refinery Distillation Systems, *Institution of Chemical Engineers, 81*, 2003,147-152

[3] H. Al-Muslim and I.Dincer, Thermodynamic Analysis of Crude Oil Distillation Systems. *Int. J. Energy Reserarch, 29*, 2005, 637-653

[4] M.Douani, S.Terkhi, and F.Quadjenia, Distillation of a Complex Mixture. Part II: Performance Analysis of a Distillation Column Using Exergy, *Entropy,9*, 2007, 137-151

[5] R.Rivero, Application of the Exeryg Concept in the Petroleum Refining and Petrochemical Industry, *Energy Conversion and Management. 43*, 2002, 1199-1220

[6] A.Thernesz, Z.Varga, I.Rabi, Z. Czaltig and M.Lorincova, Applying Process Design Software for Capacity Increasse and Revamp of Distillation Units, *Clean Tech. Environ. Policy*, 2009

[7] E. Sciubba and G. Wall, A Brief Commented History of Exergy form the Beginnings to 2004, *International Journal of Thermodynamics, 10*(1), 2007, 1-26

[8] P. Le Goff, T. Cachot, and R.Rivero, Exergy Analysis of Distillation Process', *Chemical Engineering and Technology*, 19,1996, 478–485.

[9] A.Anaya, L.M. Caraveo, V.H. Carcia, and A. Mendoza, Energetic Optimization Analysis of a Petroleum Refinery Applying Second Law of Thermodynamics', *Proceedings of the Computer-Aided Energy Systems Analysis*, ASME AES, 21,1996, 49–54

[10] R.Rivero, C. Rendon and S. Gallegos, Exergy and Exergoeconomic Analysis of a Crude Oil Combined Distillation Unit, *Energy, 29*, 2004, 1909-1927

[11] J.Szargut, D.R. Morris and F.R. Steward, *Exergy Analysis of Thermal, Chemical and Metallurgical Processes* (Hemishere Publishing Corporation: New York, 1988)

[12] R.Rivero, C. Rendon and L. Monroy, The Exergy of Crude Oil Mixtures and Petroleum Fractions: Calculation and Application, *Int. Journal of Applied Thermodynamics, 2* (3), 1999, 115-123

[13] A.N. Anozie, F.N Osuolale and A.S Osunleke, Exergy Analysis of Binary Plate Distillation Column Operations, *Int. J. Exergy*, 2009,6(5), 715–728

[14] A.N. Anozie, F.N Osuolale and T.C. Asepeeri, Exergy Analysis and Optimization of Binary Plate Distillation Column Operations, *Int. J.Exergy. 7*(5), 2010,593-606