Energy and Exergy Analysis of the Crude Oil Fractionation Units

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Received on:1/4/2010
Accepted on:7/10/2010

Abstract

The petroleum refining industry is one of the largest users of distillation technology. The crude distillation unit is one of the most important refinery operations fractionating preheated crude oil into respective product fractions like Heavy Naphtha, Kerosene, Aviation Fuel, Light Gas Oil, Heavy Gas Oil, Reduced Crude Oil, etc. It uses heat supplied at higher temperature levels, and rejects almost equal amount of heat in the condenser at lower temperature levels yielding a separation work of mixtures. Therefore, it becomes important to study the energy and exergy of the crude oil fractionation tower to analysis the energy efficiency.

The present study deals with a thermodynamics analysis, energy and exergy efficiencies and the irreversibility rate for of the crude oil fractionation tower (AFT). The results shows that the total irreversibility losses are 90.7 MW, 95% are contributed by the AFT, and 5% by the furnace, for a flow rate of 159.2 kg/s of crude oil processed. The energy efficiencies are 0.597 for the AFT, 1.0 for the furnace as we are assuming adiabatic heat transfer in the process and 0.704 for the overall system. The exergy efficiencies are 0.5867 for the AFT, 0.974 for the furnace and 0.638 for the overall system. From the values of the energy efficiencies, exergy efficiencies, and the irreversibility rate in spite of the decline of the fractionation unit equipments, it shows that the operating conditions used (especially the temperature profile and the pressure profile of the AFT and the flow rates of the different streams) gives the best results.

Keywords: Energy analysis, exergy analysis, crude oil fractionation units

تحليلات الطاقة و الاكسيرجي في وحدات تكرير النفط الخام

الخلاصة

تعتبرصناعة تكرير النفط الخام من اكثر العمليات استخداما لتكنولوجيا التقطير و التي تعتبر من اكثر الوحدات اهمية في مصافي النفط, حيث يتم فيها تسخين ثم تجزئة النفط الخام الى عدة مقاطع بترولية مهمة مثل النفثا الثقيلة, الكيروسين, وقود الطائرات, زيت الغاز الخفيف, زيت الغاز الثقيل, و متبقي عملية التقطير و غيرها. ان عملية التجزئة هذه تتم باستخدام مستويات عالية من الطاقة الحرارية ولذلك فان دراسة و تحليل الطاقة والاكسيرجي يعتبر مهما جدا.

ان الغرض من هذه الدراسة هي اجراء التحليلات الثرموديناميكية لبرج تجزئة النفط الخام AFT لدراسة كفاءة الطاقة و كفاءة الاكسيرجي, و معدل الخسارة الكلية وذلك لوجود كميات ضائعة من الاكسيرجي في هذه الوحدات و معداتها. لقد استخدم اسلوب تحليل الطاقة و تحديد الاداء و اختيار الامثل من الظروف المطلوب دراستها خاصة درجات الحرارة و الضغوط و معدلات الجريان لمختلف خطوط الجريان في وحدة التكرير. النتائج المستحصلة بينت بان الخسارة الكلية في الاكسيرجي في الوحدة تبلغ (90.7ميكا واط) وذلك لمعدل

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https://doi.org/10.30684/etj.28.20.2
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جريان يبلغ (159.2) كغم/ثانية من النفط الخام المراد تكريره حيث تمثل هذه الخسارة بمكونات وحدة التكرير متمثلة بفرن تسخين النفط الخام و برج التكرير الجوي AFT حيث ان النسبة الكبيرة من الخسارة تحصل في البرج حيث تحدث بة عمليات الفصل. و عند افتراض الظروف الاديباتيكية لانتقال الحرارة , فان كفاءة الطاقة كانت 0.597 لوحدة AFT و 1.00 للفرن. لقد اعطت الظروف التشغيلية المستخدمة في الوحدة نتائج مقبولة من الكفاءات و معدل الخسارة بالاكسيرجي.

Introduction

Exergy is defined as the maximum amount of work that can be extracted from a stream as it flows toward equilibrium. This follows the second law of thermodynamics, which states that not all heat energy can be converted to useful work. The portion that can be converted to useful work is referred to as exergy, while the remainder is called non-exergy input

Exergy analysis provides a powerful tool for assessing the quality of energy and quantifying the portion of energy that can be practically recovered. Exergy analysis uses parameters such as temperature or pressure to determine energy quality and calculate potentially recoverable energy. Exergy or energy quality, diminishes each tune energy is used in a process. For example, a large percentage of energy content can be extracted from flowing steam at high temperatures. As the steam temperature drops (e.g., after passing through a heat exchanger), the percentage of energy that can be recovered is reduced. This drop in energy quality is referred to as a loss of exergy or energy degradation. Exergy analysis is an efficient technique for revealing withers or not and by how much it is possible to design more efficient thermal systems by reducing the inefficiencies of the units in a system. Also for determine which unit of the system are most influence on its exergy efficiency [1-5].

In general, separation processes in the process industry require a large input of energy. Therefore, many kinds of thermodynamic analyses have been performed, especially for distillation columns, from the viewpoint of energy saving.

Extensive amount of exergy analysis was carried out on standard thermodynamic cycles and their application in industry such as power plants, refrigeration systems and to some extent use of solar energy. However attention is focused mostly on energy analysis for industrial processes rather than exergy analysis [6].

Abdi and Meisen, [7] studied the purification of contaminated amine solution using distillation column. They showed that by modifying the process into two-stage distillation and varying the process parameters, full recovery of pure substance can be achieved.

Doldersum,[8] used exergy analysis to prove viability of distillation process modification and showed that by decreasing the operating pressure and thus lowering operating temperature, using high pressure steam reboilers instead of furnace and splitting feed stream, total exergy losses may be reduced by 70% that directly results in a primary fuel reduction of almost 40%

and energy saving of 10% due to splitting of the feed stream.

Ji, [9] in his study was only involved in the energy analysis in terms of fuel consumption ratio to crude oil processed which was about 2%. He optimized processing of two types of crude oil, and also considered two alternatives to conventional design of crude oil distillation plant; the pre-flash design and the stripping type design.

Taprap and Ishida, [10] adopted the graphical construction called an energy utilization diagram for analysis energy transformation and exergy losses in a distillation column. The overall exergy loss on one plate of a column can be decomposed into six kinds of energy losses and are represented graphically. The concept of individual energy level was applied.

Mustapha, et. al., [11] analyzed the performance of the separation process by introducing thermodynamic concept of exergy through exergetic efficiency of the column. The results showed that the exergetic output is relatively low and the produced irreversibility fluxes are distributed throughout the whole column in a non-uniform manner. They are particularly significant in the condenser, boiler, and tray feed. The influence of various operating parameters; temperature, concentration, and irreversibility in both sections of the column, was also established.

In this study, an energy and exergy analysis of the crude oil fractionation systems is conducted and the work is extended to study the effects of the key system parameters in terms of the crude oil fractionation unit temperature, pressure, and mass flow rate of different streams on the system energy and exergy efficiencies at various conditions.

System Description

The crude oil fractionation unit has many components, e.g. crude oil furnace (F), the atmospheric fractionation tower (AFT), Figure (1) illustrate a schematic diagram of the crude oil fractionation unit that considered in the present work. There is also a heat exchanger network which is not shown in the figure, but its effect via utilizing high temperature product streams to preheat the crude oil as well as the product streams should be cooled using the crude oil feed. In the energy and exergy analysis this preheating effect is not considered taking the worst condition to maximizing the furnace duty as the plant operated for the first time, [13].

In the present model, a charged crude oil which is processed in Al-Daura refinery fractionation unit with flow rate of 159.2 kg/s (100,000 barrels/day), is considered. This crude oil have API of (32^o) consisting of 30% of Kirkuk crude oil (35.5^o API), 65% of Basrah crude oil (29.5^o API), and 5% of Naft Khana crude oil (42^o API) (stream No. 1 in the figure (1)). Crude oil is a mixture of thousands of hydrocarbons ranging from very light to very heavy components depending on the difference of the boiling temperatures. The refinery complex objective is to produce desired products, e. g. fuel gas (stream No. 12), liquid petroleum gas (LPG), (stream No. 3), light naphtha (stream No. 4), heavy naphtha (stream No. 5), kerosene (stream No. 6), light gas oil (stream No. 7), heavy gas oil (stream No. 8) and atmospheric residue (stream No. 9).

So, for the optimum separation of the fractionation unit, accurate temperature, pressure and flowrates of different streams are of paramount importance.

Energy and Exergy Analysis

There are three governing equations that are commonly used in the energy and exergy (thermodynamics) analysis of the control volume systems, namely conservation of mass equation, conservation of energy equation, and entropy generation equation, as available in some reference books (e.g. [14,15, 16]). These equations are applied to the steady-state flow conditions for the case of negligible changes in kinetic and potential energy changes with ambient conditions; T_o =25 ^oC=298.15 K, P_o=1 atm=101 kpa. For every individual component, the three conservation equations are applied to calculate the heat added, the rate of exergy losses, and the exergy efficiency. After simplifications, the mass, energy, and the exergy balance equations respectively, are:-

$\sum m_{in} = \sum m_{out}$ …….(1)

$\sum E_{in} + Q_{cv} = \sum E_{out} + W_{cv}$ ……(2)

$\sum Ex_{in} + \sum (1-T_o/T_j)\, Q_{cv} = \sum Ex_{out} + W_{cv} + I_{cv}$ ………(3)

Knowing that, energy is always conserved in a system, exergy is just converted from one form to anther like from heat to work or from heat to increase in internal energy of the system. Energy balance equation does not tell in which direction should the process go. Energy efficiency η is defined as the ratio of the energy output desired to the energy input given by the relation:-

$\eta = E_{out} / E_{in}$ …..(4)

Exergy is only conserved for reversible system. For real systems, there are always exergy losses or irreversibilities associated, and actual systems always move in the direction of decreasing exergy. Exergy loss is directly proportional to the entropy generation in the system.

Where the exergy losses from a control volume and the total exergy are given, respectively, as:

$I_{cv} = W_{cv}^{rev} - W_{cv}$. ….(5)

$Exr = U + P_o V - T_o S + \sum \mu_{oi} N_i$ ....(6)

$Exr = H - T_o S + \sum \mu_{oi} N_i = Exr_{ph} + Exr_{ch}$.....(7)

The exergy is composed of physical exergy, which is the maximum shaft power a system can produce when it is brought to the reference temperature and pressure. This exergy is dealing with mixtures, another exergy term comes into the picture, the chemical exergy, which is defined as the maximum shaft power a system of mixtures can produce when the composition of the components in the mixture are brought to the reference state. In the system studied in the present work, the reference molar composition of the components is assumed to be 1.0.

Note that the physical exergy, Exr_{ph}= H -T_o S, and the chemical exergy Exr_{ch} =$\sum \mu_{oi} N_i$, where $\mu_{oi}=h_{oi}-T_o s_{oi}$.

Introducing the exergy efficiency as:

$\Psi = \sum Ex_{out} / \sum Ex_{in}$ ….(8)

Crude Oil Heating Furnace (F)

By applying the energy equation (2), and assuming heat input is equal to the heat output (adiabatic process), to find the required fuel gas mass flow rate m_{12}:

$m_{12}=m_1 [(h_2-h_1) / (h_{12}-h_{13})$ ……(9)

The exergy efficiency is not defined for the furnace as the process here is adiabatic. Applying the exergy equation(3) to find the exergy losses (irreversibility rate), and noting that no chemical exergy will take place in the furnace, since the chemical composition of the crude oil did not change as no separation takes place in the furnace:

$I_F=m_1 (ex_1-ex_2) + m_{12} (ex_{12}-ex_{13})$….(10)

The exergy efficiency was determined from the relation:

$\Psi_F= (\sum Ex_{in}- I_F)/ \sum Ex_{in}$ ….(11)

Where the exergy input rate for the crude oil heating furnace was given by:

$\sum Ex_{in} = m_1 ex_1 +m_{12} ex_{12}$ …(12)

Atmospheric Fractionation Tower (AFT)

The heat transfer rate from the tower was found by applying the energy equation (2):

$Q_{AFT}=m_3 h_3 +m_4 h_4 + m_5 h_5 +m_6 h_6 + m_7 h_7 + m_8 h_8 + m_9 h_9 +m_{11} h_{11} – m_2 h_2 – m_{10} h_{10}$ …..(13)

The energy efficiency was obtained by applying equation (4):

$\eta_{AFT} = (m_3 h_3 +m_4 h_4 + m_5 h_5 +m_6 h_6 + m_7 h_7 + m_8 h_8 + m_9 h_9 +m_{11} h_{11}) / (m_2 h_2 + m_{10} h_{10}$ ……(14)

Using exergy equations (3) and (7), we got the physical and chemical exergy losses respectively, because of the separation process:

$I_{ph} = m_2 ex_2 +m_{10} ex_{10} –m_3 ex_3 – m_4 ex_4 – m_5 ex_5 –m_6 ex_6 – m_7 ex_7 – m_8 ex_8 – m_9 ex_9 – m_{11} ex_{11} +\sum (1-T_o/T) Q_{AFT}$ ……..(15)

$I_{ch} = m_2 ex_2 +m_{10} ex_{10} – m_3 ex_3 – m_4 ex_4 – m_5 ex_5 – m_6 ex_6 – m_7 ex_7 – m_8 ex_8 –m_9 ex_9 – m_{11} ex_{11}$ ….(16)

The exergy efficiency was found by applying equation (8):

$\Psi_{AFT} = [\sum Ex_{in} + \sum (1-T_o/T) Q_{AFT} - I_{ph}] / \sum Ex_{in}$ ……(17)

Where the exergy input to the atmospheric fractionation tower is:

$\sum Ex_{in} = m_2 ex_2 +m_{10} ex_{10}$ …..(18)

Overall System (ALL)

Taking the whole unit, we noticed that the heat transfer occurs as follows:

$E_{in} = m_1 h_1 + m_{10} h_{10} + m_{12} h_{12}$ ..(19)

$E_{out} = m_3 h_3 +m_4 h_4 +m_5 h_5 + m_6 h_6 +m_7 h_7 +m_8 h_8 + m_9 h_9 +m_{11} h_{11} + m_{13} h_{13}$ ..….(20)

The overall efficiency was obtained from equation (4):

$\eta = E_{out} / E_{in}$

The total irreversibility rate is the summation of the irreversibility rates of the individual components:

$I_{ALL} = I_F + I_{AFT}$ …….(21)

The exergy efficiency was obtained by applying equation (8):

$\Psi_{ALL} = [\sum Ex_{in} + \sum (1-T_o/T) Q_{ALL} - I_{ALL}] / \sum Ex_{in}$ ……(22)

Where

$\sum Ex_{in} =m_1 ex_1 + m_{10} ex_{10} + m_{12} ex_{12}$ ……..(23)

$\sum Ex_{out} =m_3 ex_3 + m_4 ex_4 + m_5 ex_5 + m_6 ex_6 + m_7 ex_7 + m_8 ex_8 + m_9 ex_9 + m_{11} ex_{11} +m_{13} ex_{13}$ ……..(24)

Results and Discussion

The calculations are run for the actual operating conditions of Al-Daura petroleum refinery fractionation plant. The input data are presented in Table 1, where the different streams are identified with their properties (temperature, pressure, flow rates and specific enthalpy and entropy). These describe the input of unit operations including the atmospheric fractionation tower (AFT) and the crude oil furnace. The results are summarized in Table 2. The compositions of the products of the fractionation tower vary substantially in the same plant depending on the properties of the

crude oil used and the operating conditions namely the fractionation tower temperature and pressure profiles.
Here, it was studied the influence of these operating conditions on AFT unit. The calculation sequence including energy and exergy analyses are conducted of the crude oil fractionation, focusing on the main devices: an AFT and the crude oil furnace, we can find the heat balance, energy efficiency, exergy efficiency, and the irreversibility rate for the individual components and the overall system. The calculation for exergy are made twice; one with neglecting the chemical exergy and the other including the chemical exergy loss inherent to separation process. This is done to see how much is the contribution of chemical exergy loss to total exergy loss.
The energy efficiency of the AFT is 0.597; this efficiency is low because the main separation takes place there. The energy efficiency of the overall system is 0.704. the energy efficiency of the furnace is 1.0 as we are assuming adiabatic heat transfer in the furnace.
The highest irreversibility (exergy losses) occur in AFT with 95% of the total irreversibility losses. This is again because the main separation takes place in the AFT. Those losses are composed of the physical and chemical exergy losses. The chemical exergy losses are 30.8% of the total exergy losses. In the crude oil furnace, the irreversibility loss is 5%, only physical exergy losses are presented here as there is no separation process in the furnace.
The components that contribute most to the irreversibility losses have the least exergy efficiency. The exergy efficiencies are 0.974 for the furnace and 0.5867 for the AFT, and 0.638 for the overall system. Knowing that, the efficiency of the overall system is not equal to the product of the efficiencies of the individual components.

Conclusions

In this work, energy and exergy analyses of the crude oil fractionation unit model is conducted. The model is applied successfully for system consist of the crude oil furnace, and the atmospheric fractionation tower (AFT) in order to find the effect of the operating conditions on the energy efficiencies, exergy efficiencies and the irreversibility rate of the individual components and the overall system.
The total irreversibility losses are 90.7 MW, 95% are contributed by the AFT, and 5% by the furnace. The highest irreversibility losses occur in the AFT as the main separation takes place there, 29.3% of the losses are due to chemical exergy losses associated with the separation process itself. The rest of the losses are due to the physical exergy losses mainly because of the temperature difference. The energy efficiencies are 0.597 for the AFT, 1.0 for the furnace as we are assuming adiabatic heat transfer in the process and 0.704 for the overall system. The exergy efficiencies are 0.5867 for the AFT, 0.974 for the furnace and 0.638 for the overall system. From the values of the energy efficiencies, exergy efficiencies, and the irreversibility rate inspite of the decline of the fractionation unit equipments, it shows that the operating conditions used (especially the temperature profile and

the pressure profile of the AFT and the flow rates of the different streams) gives the best results.

References

1. Rosen, M. A., Dincer, I, (1997). On Exergy and Environmental Impact, International Journal of Energy Research, Vol. 21, pp 643-654.
2. Ayres, R. U., Ayres, L. W., Martinas, K.,(1998). Exergy Weste Accounting and Life-Cycle Analysis, Energy, Vol. 23,pp 355-363.
3. Dincer, I., (2002). The Role of Exergy Policy Making, Energy Policy, Vol. 30, pp 137-149.
4. Rosen, M. A., Dincer, I., (2001). Exergy as the Confluence of Energy Environmental and Sustainable Development, Exergy – An International Journal, Vol. 1, pp 1-11.
5. Wall, G., Exergy – A useful Concept, Ph.D. Thesis, Chalmers University of Technology, S-41296 Gotenberg, Sweden, (1986).
6. Cornelissen, R. L., (1997). Thermodynamics and Sustainable Development, Ph.D. Thesis, University of Twente, the Netherlands.
7. Abdi, Majid A., Meisen, A., (1999). A novel Process for Diethanolamine Recovery from Partially Degraded Solutions; Process Analysis. Ind. and Eng. Chem. Research No. 38, Vol. 8: pp 3105-3114.
8. Doledersum, A., (1998). Exergy Analysis Proves Viability of Process Modifications. Energy Conversion and Management, Vol. 39, pp 1781-1789.
9. Ji, S., (2001). Optimal Design of Crude Oil Distillation Plants, Norman.
10. Taprap R., and Ishida, M., (1996). Graphic Exergy Analysis of Processes in Distillation Column by Energy – Utilization Diagrams, AIChE J., Vol. 42, No. 6.
11. Mustapha, D., Sabria, T., and Fatima, O.,(2007). Distillation of a Complex Mixture; Performance Analysis of a Distillation Column Using Exergy, Entropy, Vol. 9: pp 137-151.
12. Anaya A., Caraveo, L. M., Carcia, V. H., Mendoza, A.,(1990). Exergetic Optimization Analysis of a Petroleum Refinery Applied Second Law of Thermodynamics. Processing of the Computer – Aided Energy Systems Analysis. ASME, AES, Vol. 21, pp 49-54.
13. Dincer, I., and, Rosen, M. A.,(2007). Exergy; Energy, Environmental and Substainable Development, Elsevier.
14. Sonntage, R. E., Borgnakke, C., and Van Wylene, G. J.,(2003). Fundamentals of Thermodynamics, Joun Wiley and Sons Inc., 6th ed.
15. Bejan A.,(1988). Advanced Engineering Thermodynamics, a Wiley Interscience Publ.
16. Van Wylene, G. j. Sonntage R. E., and Borgnakke, C.,(1994). Fundamentals of Classical Thermodynamics, John Wiley and Sons Inc., 4th ed.

Nomenclature

AFT	Atmospheric Fractionation Tower
ch	chemical
cv	control volume
E	Energy rate, kw

ex	specific exergy, kJ/kg
Ex	Exergy rate, kw
Exr	exergy, kJ
F	Furnace
h	specific enthalpy, kJ/ kg
I	Irreversibility rate, kw
m	mass flow rate, kg/s
N	molar ratio
o	reference condition
P	Pressure, kpa
ph	physical
Q	heat transfer rate, kw

rev	reversible process
S	Entropy rate, kw/K
s	Specific entropy, kJ/kg. K
s_o	Specific entropy of formation,
T	temperature, K
v	specific volume, m^3/ kg
W	Work rate, kw
η	energy efficiency
μ	chemical potential, kJ/kg
Ψ	exergy efficiency

Table (1) Parameter Presentation for the Operating Conditions

State	Stream	Phase	Temperature (°C)	Pressure (kpa)	Mass Flow Rate (kg/s)	Specific Enthalpy (kJ/kg)	Specific Entropy (kJ/kg.°K)
1	Crude Feed	L	25	101	159.2	34.4	4.44
2	Heated Crude	Mixed	346	101	159.2	1040	6.616
3	Off Gas	G	73	205	2.55	761	4.216
4	Light Naphtha	L	73	205	22.2	198	1.62
5	Heavy Naphtha	L	121	208	7.1	326	3.0
6	Kerosene	L	187.8	210	19.14	512	3.04
7	Light Gas oil	L	221	215	21.62	535	4.266
8	Heavy Gas oil	L	326.7	225	60.4	837	5.016
9	Atmospheric Residue	L	343.4	235	26.19	802	6.557
10	Steam	G	350	506.5	1.7	3172.3	7.65
11	Water	L	73	101	1.6	284	0.96
12	Fuel Gas in	G	1100	101	188.12	1180	7.987
13	Flue Gas out	G	350	101	188.12	329	7.1

Table (2) Model Results for the Operating Conditions

Results	Furnace	AFT	ALL
$\sum E_{in}$ (kw)	227460	170961	232853
$\sum E_{out}$ (kw)	227460	102031	163923
Q_{cv} (kw)	0	68930	68930
η	1	0.597	0.704
$\sum Ex_{ph,in}$ (kw)	172237	144304	177294
$\sum Ex_{ph,out}$ (kw)	167737	84664	113165
I_{ph} (kw)	4500	59640	64129
$\sum Ex_{in}$ (kw)	172237	144304	177294
$\sum Ex_{out}$ (kw)	167737	58087	86587
I (kw)	4500	86217	90707
%I	5	95	100
Ψ	0.974	0.5867	0.638
I_{ch} (kw)	0	26577	26577
$\%I_{ch}$	0	30.8	29.3

AFT: Atmospheric Fractionation Tower, ALL: overall of Fractionation Unit

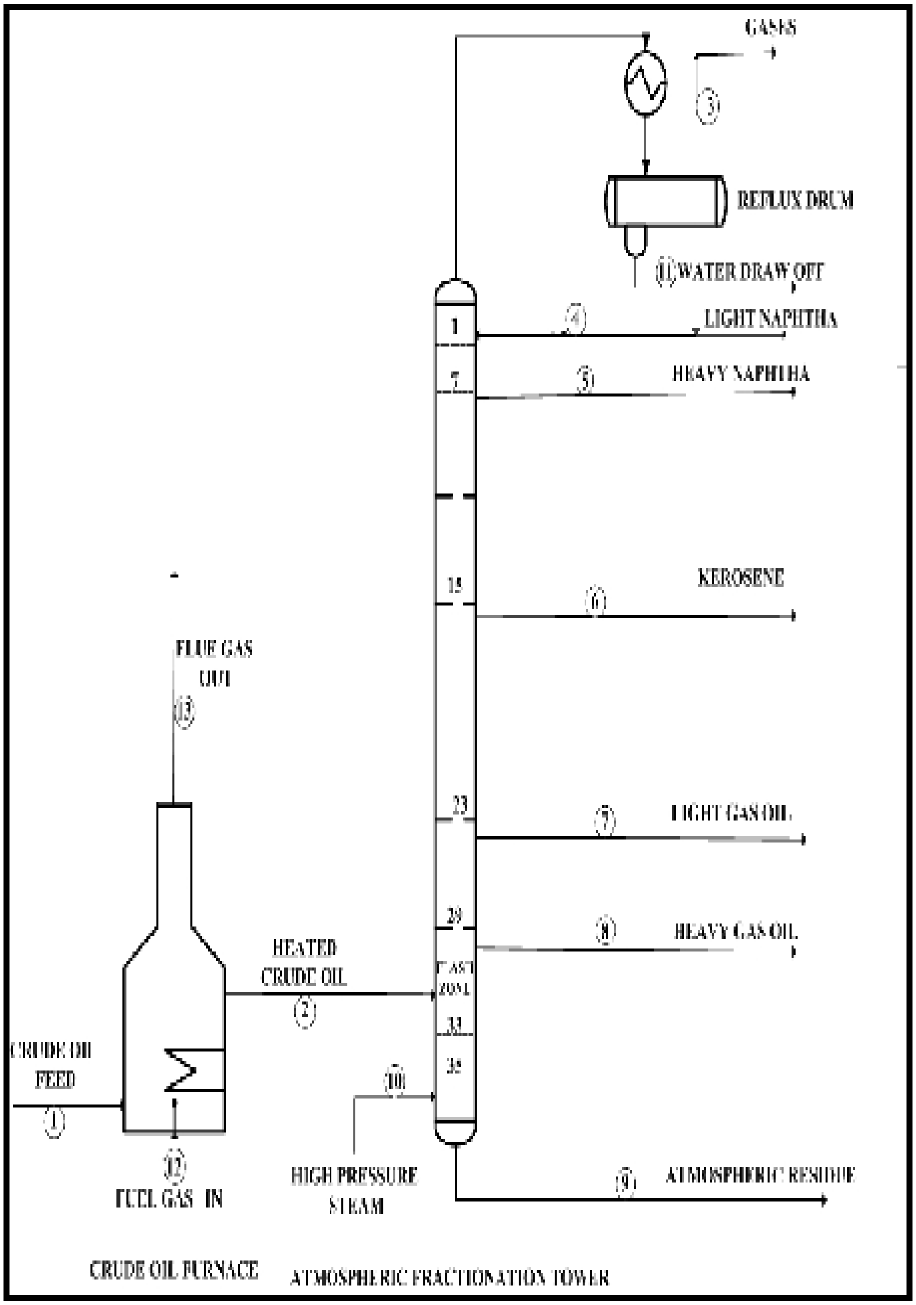

Figure (1) Model of a Crude Oil Fractionation Unit