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Determination of Plate Efficiency of Rectification Column in Refinery Operations

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ABSTRACT

The determination of plate efficiency of rectification column for the separation of Bonny Light Crude Oil into its fractions was studied. The atmospheric distillation column of a typical Refinery (PHRC) was used in determining the efficiencies of the bubble-cap plate of the column. It was observed that the efficiency of the plates below the feed plate varies, but above the feed plate, it increases up the top of the column and was highest at top plate. The total number of ideal and actual plates was found to be 7. The Murphree equation for plate efficiency was used to determine the overall efficiency of the column with the aid of the McCabe-Thiele diagram to be 93.9 %. This work has shown the efficiency, reliability and integrity of the plant.

Keywords: *material balance, hydraulic calculations, energy balance, mass transfer, flooding.*

I. INTRODUCTION

The increase in demand for petroleum products has given strong concern to chemical engineers. The Engineers in meeting the demands of consumers or, end use of these products, ensure that equipments for the production of these products are designed to achieve the desired goals.

Most separation processes in the chemical industries are unit operation processes (the breaking up of complex processes into individual physical steps). Such unit operation processes include centrifugal systems, distillation, gas absorption, humidification, sedimentation, etc. [1]

The separation of liquid mixtures into its various components in the process industries uses distillation process, which is the key operation in the refinery. Thus, distillation is a process by which liquid or vapour mixtures are separated into its component fractions. The distillation processes for separation of mixtures is carried out in a plate column in which each plate constitutes a single stage. The plates are installed within the column and spaced evenly; this determines the height of the column. The plates or trays provide intimate mixing between the vapour and liquid streams suitable for handling of the desired vapour and liquid flow rates without excessive flooding. [2]

While designing a distillation column, the engineers are expected to achieve the desired products purity at minimum cost and to provide constant product purity even when there is variation in feed compositions. [3] Distillation plates are designed with openings. These openings allow the passage of vapours from the plate below to the top plate and bubbles the liquid that is on the top tray. The liquid on the plates boils and the vapour condenses. The vapour that bubbles through the liquid on the plate comes from the plate just below. The vapour condenses as a result of the liquid on the plate which is cooler than the vapour from the plate below. Some of the liquid on the plate boils off by heat of condensation and the vapour goes up to the next plate above. The main function of the plate is to bring about mixing that the vapour of composition Y_n, approaches equilibrium with the liquid of composition X_n. [5] In most operations, distillation column is actually constructed of plates which usually do not function perfectly [6]. Thus, the vapour leaving an actual plate is usually weaker in volatile constituents than vapour in equilibrium with the liquid leaving the plate. However, before applying the McCabe-Thiele method or the enthalpy composition method to an actual case, it is pertinent to convert the number of theoretical plates to actual plates. The factor use for this conversion is known as 'Plate Efficiency'. The plate efficiency determines the actual number of plates (trays) required for a particular separation duty. [6] The Murphree plate efficiency gives the efficiency of a single plate based on vapour-phase compositions for the n^{th} plate in a fractionating column (numbered from bottom to the top). The Murphree plate efficiency is defined as the ratio of the actual separation achieved to that which would be achieved in equilibrium stage. The vapour and liquid streams are taken to be perfectly mixed compositions. [7]

Plate efficiency plays an important role in the design of distillation column. For the desired separation of mixtures to be achieved in a distillation process, the vapour leaving a plate in the column must be equal to the liquid leaving that plate. Therefore, the actual number of plates required for a particular separation duty is determined by the efficiency of the plate. This implies that any factor that causes a decrease in the efficiency of plate will definitely change the performance of the column. So, it is important to determine the efficiency of plate column before carrying out the actual construction/installation of distillation column for separation of mixture of crude oil in the refinery. By so doing, it is possible to separate crude oil mixtures that will yield the required product purity.
The objective of this work is to determine the plate efficiency of rectification column in Port Harcourt Refinery for the

separation of crude oil fractions, owing to the demand for high product purity, such that when produced it will meet the required set standards, whether sale-oriented or process oriented.

It is worth noting that the actual number of plates required for a particular separation duty is determined by the efficiency of the plate. Thus, any factor that causes a decrease in plate efficiency will also change the performance of the column. Plate efficiency is affected by fouling, wear and tear as well as corrosion, and the rate at which these occur depends on the properties of the liquids being processed. Thus plate should not only be designed and constructed with appropriate materials specified, but also monitored closely the reliability and performance of prevailing process design parameters.

II. METHODOLOGY

The methodology adopted in this work involved the use of material and energy balances of the column of a typical refinery plant, data acquisition from the plant, application of the data with known design equations, thermodynamics and hydraulic calculations with Murphrey efficiency phenomenon.

Murphree Plate Efficiency

For a vapour-liquid separation process, considering that both liquid and vapour phases are mixed perfectly, a measure of the efficiency of distillation for the composition of the vapour on stage *n*, is defined by Murphree [2] as:

$$E_m v = \frac{y_n - y_{n-1}}{y_e - y_{n-1}} \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad (1)$$

If the concentrations in the liquid streams are used, then the plate efficiency is given by:

$$E_m l = \frac{x_{n+1} - x_n}{x_{n+1} - x_e} \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad (2)$$

Equations 1 and 2 represent the change in composition on a stage with respect to that change when there is a thermodynamic equilibrium between the liquid and the vapour phases. In the equation, y_n and x_n are the vapour and liquid compositions on stage n respectively, and y_e, x_e are the composition of vapour and liquid phases that would be in equilibrium with the other phases that actually leave the stage *n*.

In general, these efficiencies are less than unity; however, in a big diameter column, the liquid or vapour leaving a plate has a slightly different composition than the liquid or vapour that reaches the next stage [7]. According to the definition, this results to efficiency greater than one hundred percent.

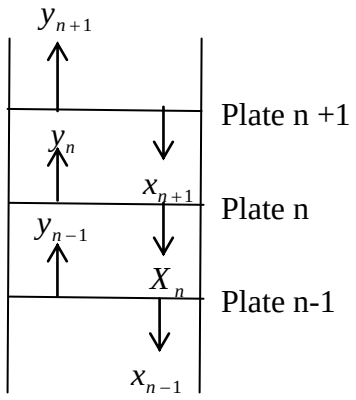

Figure 1: Composition of liquid and vapour streams from plates

When describing a mathematical model of a liquid vapour separation process, the liquid and vapour phases are related by the equilibrium constant:

$$y_n = K_n x_n \quad - \quad - \quad - \quad - \quad - \quad - \quad (3)$$

Or in terms of component flow rates as:

$$K_{i,n} = \frac{L_{i,n} - V_{i,n}}{\Sigma L_{i,n} - \Sigma V_{i,n}} \quad - \quad - \quad - \quad - \quad - \quad (4)$$

Where x, y are component *i* liquid and vapour molar composition respectively, and L and V component i molar flow rates on each stage n. Using these equations and the vapour Murphree stage efficiency equation, we have:

$$E_m V = \frac{V_{i,n} - V_{i,n-1}\dfrac{\Sigma V_{i,n}}{\Sigma V_{i,n-1}}}{\dfrac{K_{i,n}\Sigma V_{i,n}}{\Sigma L_{i,n}} L_{i,n} - V_{i,n-1}\dfrac{\Sigma V_{i,n}}{\Sigma V_{i,n-1}}} \quad - \quad - \quad - \quad (5)$$

Another approach to incorporate the Murphree efficiency into the model is to work with the vapour component flow rates, $V_{i,n}$ and the molar compositions, and then normalize the results for the new ones, $Y_{i,n}$ this is given as follows:

$$Y_{i,n} = E_m V\left(K_{i,n} X_{i,n} - Y_{i,n-1}\right) + Y_{i,n-1} \quad - \quad - \quad - \quad - \quad (6)$$

Where:

$$Y_{i,n} = \frac{V_{i,n}}{\Sigma V_{i,n}} \; ; X_{i,n} = \frac{L_{i,n}}{\Sigma L_{i,n}}$$

Overall Column Efficiency

The overall column efficiency, also known as overall plate efficiency is defined as the ratio of number of ideal stages to the number of real stages. This is expressed as:

$$E_O = \frac{number\ of\ \ ideal\ \ stages}{number\ \ of\ real\ \ stages} \quad - \quad - \quad - \quad (7)$$

An estimate of the overall column efficiency will be required when the design method used gives an estimate of the number of the ideal stages needed for the separation. [3]

For the idealized situation where the operating lines and the equilibrium line are straight, the overall column efficiency and Murphree plate efficiency are related by an equation developed by Lewis: [3]

$$E_O = \frac{Log\left[1 + E_m v\left(m\frac{V}{L} - 1\right)\right]}{Log\left(m\frac{V}{L}\right)} \quad - \quad - \quad - \quad (8)$$

Where m = slope of the equilibrium line
L = molar flow rate of the liquid
V = Molar flow rate of the vapour

III. MATERIAL AND ENERGY BALANCE

The material and energy balance will be considered for the rectifying (top) and stripping (bottom) sections as well as over the stages in the rectification column.

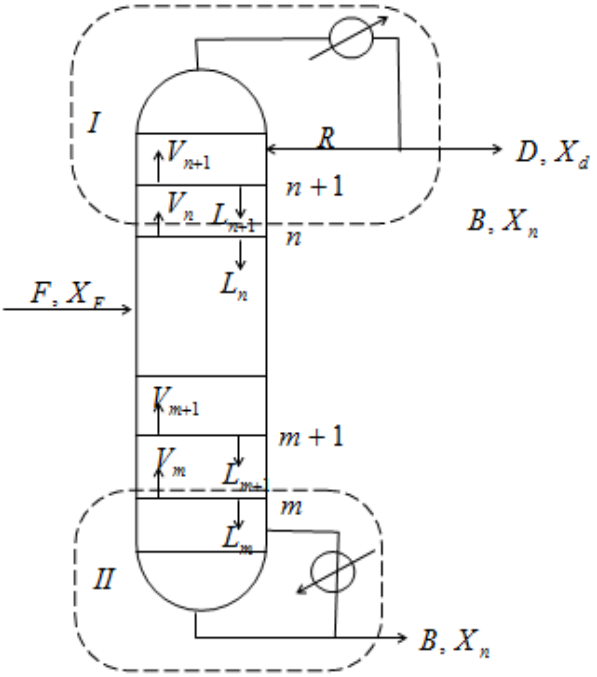

Figure 2: Flows in a column

The material balance over the column can be obtained by taking material balance round the entire column as follows:
Inflow of material = outflow of material

$$F = D + B \quad -- \quad -- \quad -- \quad -- \quad -- \quad -- \quad (9)$$

Thus, for component i in the feed mixture, withdrawn say, as overhead product, we write the component balance equation as:

$$FX_f = DX_d + BX_b \quad - \quad - \quad - \quad (10)$$

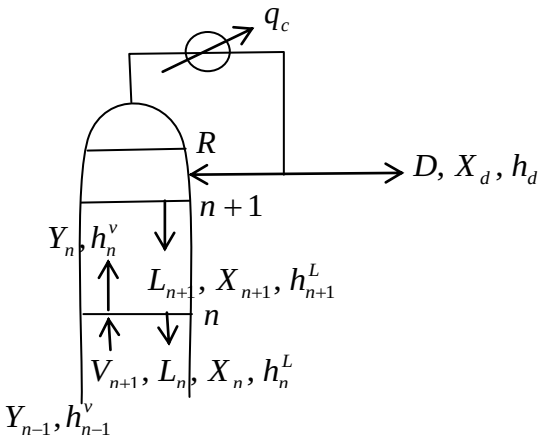

Figure 3: Column flows and composition above feed point

Figures 3 is obtained by considering Loop I in figure 2 above, which is the top section of the column, and taking material balance round the section we will obtain as follows:

$$V_n = L_{n+1} + D \quad - \quad - \quad - \quad - \quad - \quad (11)$$

Expressing equation 11 in terms of molar composition for the more volatile component gives:

$$y_n V = L_{n+1} + DX_d$$

$$\text{or} \qquad y_n = \frac{L_{n+1}}{V_n} X_{n+1} + \frac{D}{V_n} Xd \quad - \quad - \quad - \quad - \quad (12)$$

Equation 12 relates the composition of the vapour rising to the plate to the composition of liquid on any plate above the feed. Since it is assumed that the molar overflow of liquid is constant, it follows that $L_{n+1} = L_{n-1} = L_n$
Thus equation 12 can be re-written as:

$$y_n = \frac{L_n}{V_n} X_{n+1} + \frac{D}{V_n} Xd \quad - \quad - \quad - \quad - \quad (13)$$

We can also write equation 13 in terms of reflux ratio R, noting that

$$R = \frac{L}{D} = \frac{L_n}{D} \quad - \quad - \quad - \quad - \quad - \quad (14)$$

By dividing each term in the numerator and denominator in the right hand side of equation 13 by D, yields:

$$y_n = \frac{\frac{L_n}{D} X_{n+1} + \frac{D}{D} Xd}{\frac{V_n}{D} + \frac{V_n}{D}} Xd \quad - \quad - \quad - \quad - \quad (15)$$

Combining equation 11 and 15, yields

$$y_n = \frac{\frac{L_n}{D} X_{n+1}}{\frac{L_n}{D} + \frac{D}{D}} + \frac{\frac{D}{D}}{\frac{L_n}{D} + \frac{D}{D}}$$

$$y_n = \frac{RX_{n+1}}{R+1} + \frac{xd}{R+1} \quad - \quad - \quad - \quad - \quad (16)$$

The energy balance equation can be written in terms of total stream enthalpies as:

$$V_n h_n^v = Lnh_n^L + Dh_d + q_c \quad - \quad - \quad - \quad - \quad (17)$$

where q_c is the heat removed by the condenser.

Similarly, taking material and energy balances for the total streams on plate m, as indicated by loop II (bottom section) in figure 2 yields

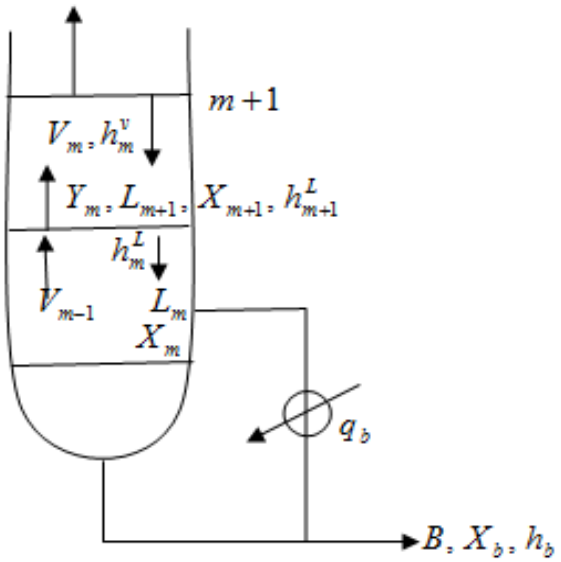

Figure 4: Column flows and compositions below feed point

$$V_m = L_{m+1} - B \quad - \quad - \quad - \quad - \quad (18)$$

In terms of molar composition, we write equation 18 as:

$$y_m V_m = L_{m+1} X_{m+1} - \frac{B}{V_m} X_b \quad - \quad - \quad - \quad (19)$$

The energy balance equation for the bottom section can be written as:

$$V_m h_m^v = L_m h_m^L - Bh_b - q_b \quad - \quad - \quad - \quad - \quad (20)$$

Where q_b is the reboiler heat added to plate m.

Equation 19 is the corresponding relation between the composition of the vapour rising to a plate and the liquid on the plate m, equations 13 and 19 are known as the operating line equations.

In order to calculate the change in composition from one plate to the next, the equilibrium data are used to find the compositions of the vapour above the liquid, and the enrichment terms to calculate the composition of the liquid on the next plate. This method may then be repeated up the column, using equation 13 for sections above the feed point, and equation 19 for sections below the feed point [3].

Evaluation of Design Parameters

The data given in Table 1 below were obtained from Port Harcourt Refining Company Limited (PHRC).

Table 1: Mass flow rate and temperature of Bonny light Crude Oil and its products

S/N	Component	Mass Flow Rate (Kg/hr)	Temperature (°C)
1.	Bonny Light Crude Oil (feed)	836,240	343
2.	LPG	72,800	108
3.	Naphtha	129,980	131
4.	Kerosene	133,640	192
5.	Light Diesel Oil (LDO)	147,638	286
6.	Heavy Diesel Oil (HDO)	169,800	317
7.	Atmospheric Residue (AR)	182,382	329
8.	Steam	90,000	400

Material Balance Calculation

Rate of input of material = Rate of output of material (21)

Thus:
Rate of input of material = flow rate of crude oil feed, F (22)
Rate of output of material = flow rate crude oil products (23)

= LPG + Naphtha + Kero + LDO + HDO + AR (24)

Therefore, we have that:

F = LPG +Naphtha + Kero + LDO + HDO + AR (25)

Substituting the respective mass flow rates of the feed and the products given in table 1 into equation 25, we have:

836240 = 72800 + 129980 + 133640 + 137638 + 169800 + 182382 = 836240 kg/hr.

Hence, since the sum of the flow rates of the products is equal to the flow rate of the crude oil feed, it follows that the material balance is satisfied.

IV. RESULTS AND DISCUSSIONS

The result of the efficiency of each plate of the rectification column was calculated and discussed.

Figure 5 is the equilibrium diagram for vapour-liquid relationship, which was used to determine the number of ideal stages in the column. Figure 6 is the detailed diagram for vapour-liquid equilibrium relationship used for the calculation of efficiency of each plate, which in turn was used to calculate the efficiency of the overall column. The dotted curve on the diagram describes the relationship of the composition of the vapour y_e that is in equilibrium with the liquid composition x_e. Similarly, the bottom and top operating line equations are indicated by the straight lines equations on the diagram. x_f on figure 5 indicates the composition of LPG in the feed.

The simplest way to gain efficiency is to increase the number of trays within a given section by reducing the spacing between trays. For instance, a 4- for – 3 tray revamp (e. g., replacing 18 trays on 24- in. spacings with 24 trays on 18-in. spacing) increases the number of theoretical stages (NTS) of a section by 33%. Since capacity decreases with lower tray spacing, higher performance (i.e., higher-capacity) trays are usually needed to handle the capacity while delivering the same tray efficiency per tray [9].

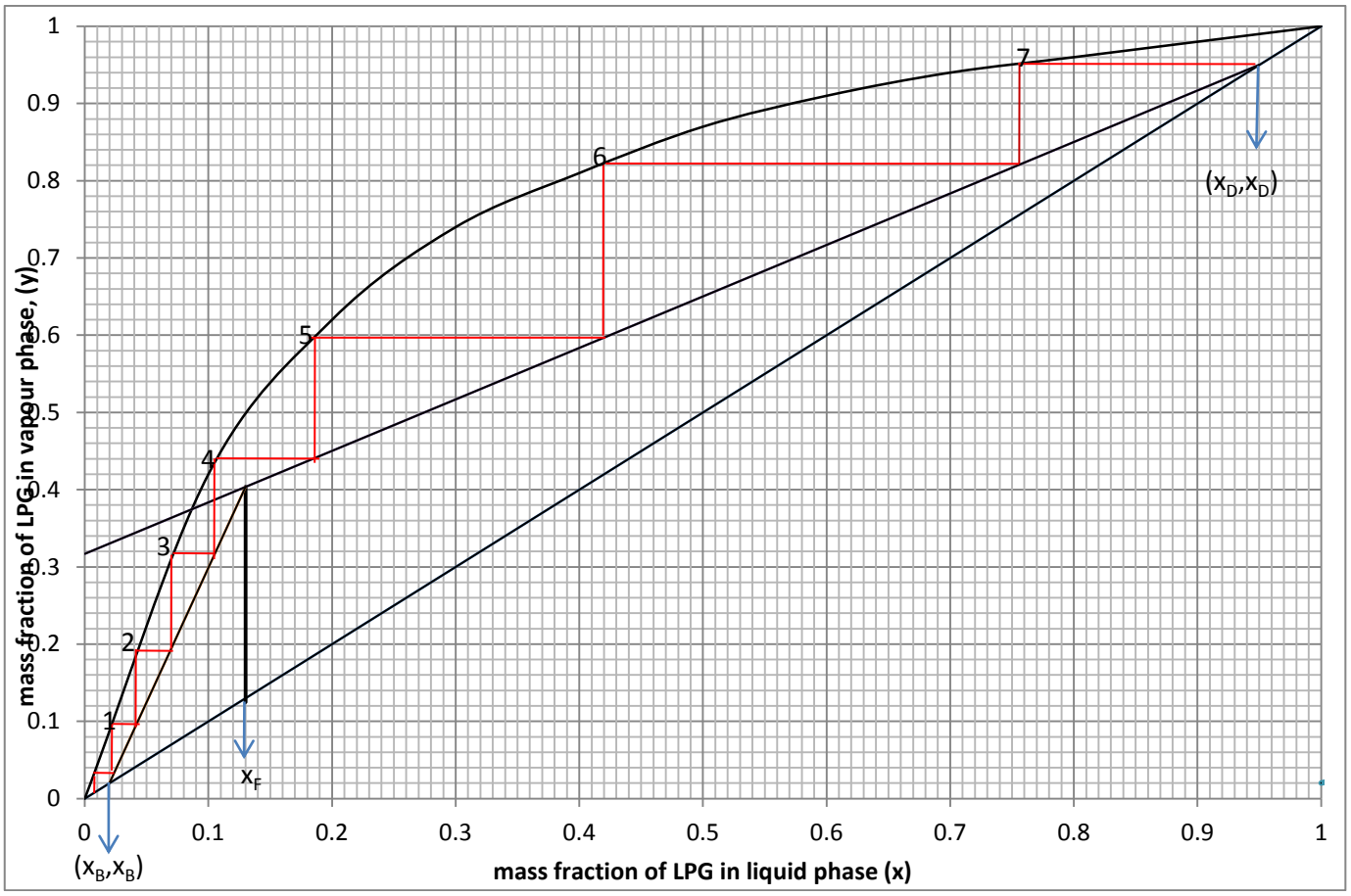

Fig. 5: Vapour-Liquid Equilibrium diagram for determination of number of stages.

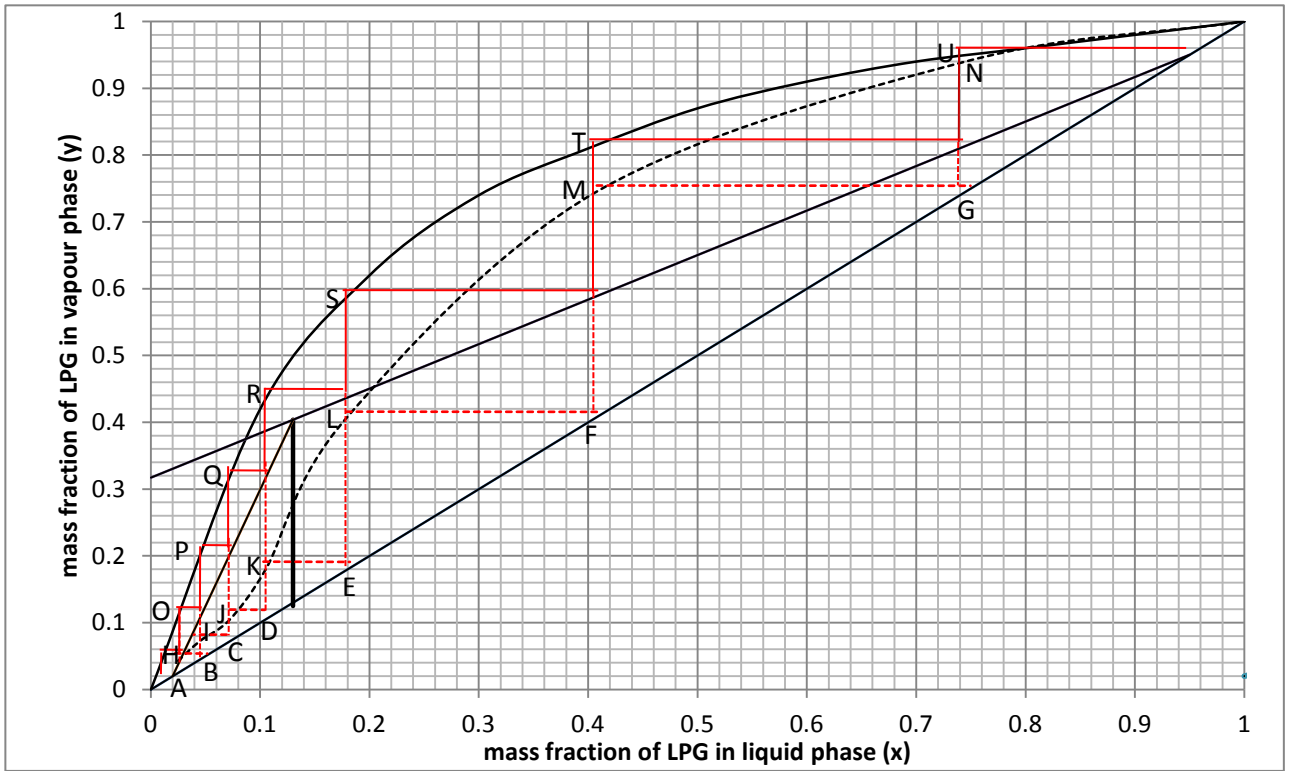

Fig. 6: Vapour-Liquid Equilibrium diagram for determination of plate efficiency

The determination of plate efficiency from Figure 6 is carried out as follows:

For Plate 1:

$$E_{ml} = \frac{AH}{AO} = \frac{0.02}{0.09} = 22.22\%$$

For Plate 2

$$E_{ml} = \frac{BI}{BP} = \frac{0.032}{0.160} = 20.00\%$$

For Plate 3

$$E_{ml} = \frac{CJ}{CQ} = \frac{0.032}{0.248} = 0.1290 = 12.90\%$$

For Plate 4

$$E_{ml} = \frac{DK}{DR} = \frac{0.074}{0.332} = 22.29\%$$

For Plate 5

$$E_{ml} = \frac{EL}{ES} = \frac{0.220}{0.404} = 54.46\%$$

For Plate 6

$$E_{ml} = \frac{FM}{FT} = \frac{0.340}{0.410} = 82.93\%$$

For Plate 7

$$E_{l} = \frac{GN}{GU} = \frac{0.190}{0.210} = 90.48\%$$

The overall column efficiency is calculated using equation 8.
That is,

$$E_O = \frac{Log\left[1 + E_{mv}\left(m\frac{V}{L} - 1\right)\right]}{Log\left(m\frac{V}{L}\right)}$$

where $E_{mv} \equiv E_{mL}$

From the calculation above, the efficiency of the top plate (plate where LPG is withdrawn) is 90.48%.

Thus, $E_{mv} \equiv E_{Ml} = 90.48\%$

$= 0.9048$

$L = L_n = 153263.16$kg/hr

$V = V_n = 229894.74$kg/hr

m = Slope of the equilibrium line

The slope m of the equilibrium curve is obtained by taking tangent at points on the equilibrium curve and then calculating the average. From the tangents taken from the figure 6, the average slope was calculated to be 1.899.

Therefore $m = 1.899$

Hence, substituting the values of L_n, V_n E_{ml} and m into equation 8, we have:

$$\frac{\log\left[1 + (0.9048)\cdot\left(1.899\frac{229894.74}{153263.16} - 1\right)\right]}{\log\left(1.899\frac{229894.74}{153263.16}\right)} = 0.939$$

$$\therefore \quad E_O = 0.939 = 93.9\%$$

V. CONCLUSION

The work has shown that to gain high efficiency of separation in a distillation column requires increase in the number of trays within a given section by reducing the spacing between trays. However, optimization principle is required to obtain optimum results. This could form the subject matter for further work on the plant.

The efficiency values obtained for plates 1, 2, 3 and perhaps plate 4 shows that the column requires adequate maintenance of the plates. There may be other sections of the plant that require thorough investigation for proper performance.

NOMENCLATURE

B – Bottom product
D – Distillate (top product)
E_m – Murphrey efficiency
E_o – Overall efficiency
F – feed
h_d , h_b, h_f - enthalpies at the distillate, boiler and feed respectively
q_b , q_c - the heat removed by the boiler and condenser respectively.
R - reboiler
x_b - liquid compositions in the boiler
x_d - liquid compositions in the distillate
x_n , x_{n+1} – liquid compositions on stage n
x_e - compositions of liquid phase that is in equilibrium with other phase that leave the stage
y_n , y_{n+1} – vapour compositions on stage n
y_e - compositions of vapour phase that is in equilibrium with other phase that leave the stage

REFERENCES

[1]. Adeymo, S.A. Olumati, I.N., Sadiz, A.A. (2009). In-House course on Dynamic Training Simulator-DTS, Port Harcourt Refining Company (PHRC) Limited.

[2]. Christic, John Geanko (2003). Transport processes and Separation Process Principles 4th Edition. Prentice-Hall, Inc. New Jersey, USA, 700-707.

[3]. Henry, Kister Z. (1992). Distillation Design. 1st Edition McGraw-Hill. 139-144, 365-367.

[4]. Richardson, J.F., Harker, J.H., Backhurst, J.R. (2006). Coulson and Richardson's Chemical Engineering, Particle Technology and Separation Processes Vol. 2, 5th Edition. ButterWorth-Heinemann, 487 – 498, 503 – 506, 547 – 548, 556 – 566.

[5]. Russell, R.A. (1983). *A flexible and Reliable Method Solves Single-Tower and Crude Distillation - Column Problems. Chemical Engineering,* October, 53-59.

[6]. Speader, J.D., and Henley, Ernest, J. (1998). Separation process Principle. New York. Available at http://en.wikipedia.org/wiki/distillation/speaderhenley, April 21, 2011.

[7]. Spiegel, L., (2006). A new method to Assess Liquid Distributor Quality. Chemical Engineering and Processing, 1011. Available at www.google.http://lorien.ncl.as.uk/ming/distil/distilat.htm, April 21, 2011

[8]. Tham, M.T. (2003). Introduction to Distillation. Available at www.google.http://lorien.ncl.as.uk/ming/distil/distildes.htm, April 21, 2011.

[9]. Mark, P. and Daniel, R. S. (2012): Be smart about column design AIChE **CEP** Journal p. 37 Nov. 2012