AJChE 2008, Vol.8 , No. 1 , 61 – 69

Graphical Separation Performance-Exergy Analysis for Revamping of Distillation Column

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We have invented graphical representation of separation performance and the exergy loss of all subprocesses in a distillation column on material-utilization diagram (MUD). The diagram display flowrate of liquid and gas as abscissa and ln x and ln y as ordinate. This diagram is useful for qualifying and quantifying the exergy loss in a distillation column, since exergy gain and exergy loss in the liquid and gas phases as well as in the phase change, can be displayed in a single figure. This paper is proposed to apply this MUD for revamping of distillation column.

Keywords: Distillation column , exergy analysis, MUD, revamping

INTRODUCTION

Distillation remains the predominant separation technique in the chemical process industries, accounting for more than 90% of product recovery and purification applications. Its systems are well understood and are relatively easy to design and operate, but they have relatively high energy consumption. Consequently, efforts to incorporate energy saving in a distillation column are getting attractive due to the rising cost of energy. One of the promising methods for synthesizing and developing energy efficient distillation process is a graphical thermodynamic analysis. It allows the thermodynamic efficiency of the process to be quantified, the causes of thermodynamics inefficiency to be identified and inspect them to learn the important characteristics. Finally better design assistance for the process synthesis can be defined (Ognisty, 1995).

Thermodynamic analysis of distillation column is a useful representation of the energy saving potential for possible reduction in energy and exergy losses. This analyses approach can be done via the temperature-enthalpy curve (Linhoff, 1984; Ishida and Nakagawa, 1985) and exergy analysis (Kaiser and Gourlia, 1985; Taprap and Ishida, 1996).

Budiman and Ishida (1996, 1998) break overall exergy loss in distillation column into individual component and present integrated information over the whole column using IEUD. The powerfulness of this methodology is that it provides useful understanding and exergy insight, in which can confirm the quantity and quality of energy. However, effect of separation performance on the changing of exergy loss cannot be judged. Then, they have invented material-utilization diagram (MUD) methodology for disclosing internal phenomena in distillation column (2004, 2007).

Since distillation is considered a low efficiency process, it should be possible to revamp its system to improve efficiency with investment of capital and still receive a reasonable return on investment. Many options are available for revamping of distillation column, such as additional more trays, changing column diameter and installing side heating-side cooling. This paper is proposed to evaluate the available option for this purpose using MUD. By applying this graphical technique, separation performance, transfer of material, exergy loss and exergy exchange can be studied easily.

NON EQUILIBRIUM MODEL FOR DISTILLATION COLUMN

Solving problem in distillation column, generally, is based on equilibrium model, because of its simplicity and no need to consider the mass flux. To predict the behaviour more precisely, the equilibrium model is insufficient. In this paper, non-equilibrium model -sometimes called as mass transfer model- explained in the previous paper (Budiman and Ishida 2004) is applied. This model has been verified with laboratory scale experimental results (Budiman *et al*, 2004 and 2005) and pilot plant data of distillation column (Budiman *et al*, 2006). The simulation results show to have reasonably good agreement with experimental results.

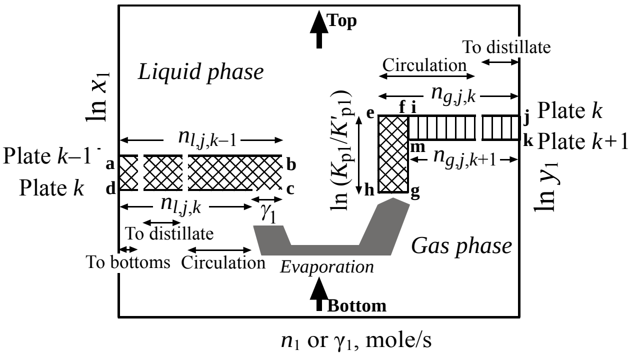
A binary mixture used in this study composes of *n*-hexane (as light component) and *n*-heptane (as heavy component). It was introduced to the column by the rate of 100 mol/s. A twenty-one perforated plate column including a total condenser (plate 1) and reboiler (plate 21) was simulated. The specifications of each plate were as follows: the area of the column was 1.0 m^2, the height of the liquid phase, Z, was 0.10 m, the number of holes per plate, N_{hole}, was 10,000, and the diameter holes D_0, was 0.003 m.

GRAPHICAL ANALYSIS USING MATERIAL-EXERGY BASED DIAGRAM

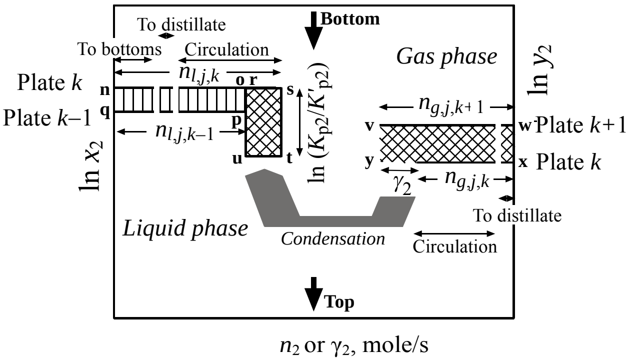
Material-utilization diagram (MUD) on a plate

Graphical technique is an excellent toll to analyze thermodynamic features and it has important role for synthesizing and developing energy efficient distillation process. One of this promising method for disclosing internal phenomena in a distillation column is material-utilization diagram (MUD). The diagram display flowrate of liquid and gas, n_j as abscissa and $RT_0 \ln x_j$ as ordinate for the liquid phase and $RT_0 \ln y_j$ for the gas phase; (a) for light component and (b) for heavy component. Since RT_0 is constant, we simplify the ordinate become ln x and ln y, so the real value should be multiplied by RT_0. Detail explanation can be found in the previous paper (Budiman and Ishida, 2004).

Figure 1 shows MUD on a plate. The exergy loss of mixing for the light component in the liquid phase is shown as area **abcd**, in (a), which is shaded by crossed lines. On the contrary, for the heavy component, the concentration increases, giving rise to exergy gain **nopq** in (b), which is shaded by vertical lines. Consequently, the difference **abcd-nopq**, indicates the net exergy loss of mixing in the liquid phase. For the gas phase, the heavy component yields exergy loss, **vwxy**, while the light component yields exergy gain, **ijkm**. The net exergy loss of mixing in the gas phase is given by the difference, **vwxy**-**ijkm**.



(a) Light component



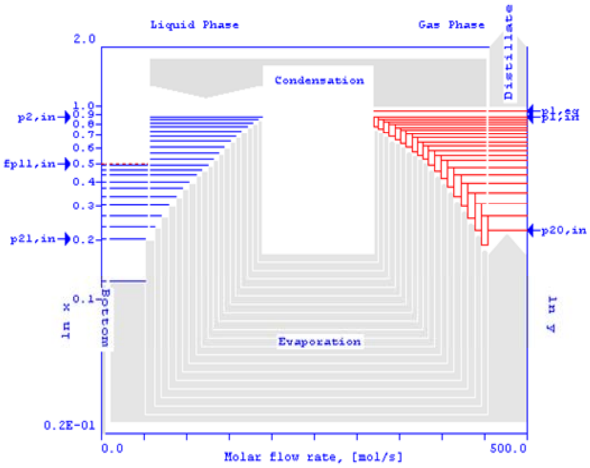
(b) Heavy component

Figure 1. Material Utilization Diagram on a Plate

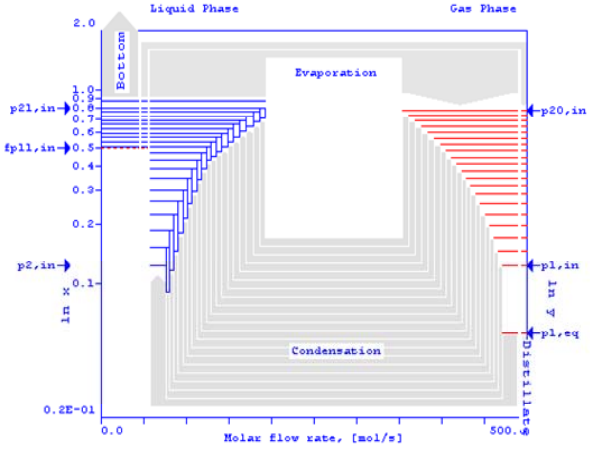
The exergy loss caused by evaporation of light component 1 is represented by shaded area **efgh** in (a). The height **eh** (or **fg)** is ln (K_{p1}/K_{p1}'), where this value indicates the ratio between the equilibrium constant K_{p1} (=$p_{1,eq}/x_{1,eq}$) and a similar constant at the output state K_{p1}' (=$p_{1,out}/x_{1,out}$). For exergy loss caused by condensation of heavy component 2 is represented by shaded area **rstu** in (b). The height **ru** (or **st)** is ln (K_{p2}/K_{p2}'). It is to be noted that the heights **eh** and **ru** can be used as a measure for deviation of the output state from the equilibrium and they indicate the driving forces of evaporation of component 1 and condensation of component 2.

MUD over the whole column

As the base case, the mixture with the reflux ratio, R= 3.0 and flowrate of distillate, D= 50 mol/s is introduced at the middle of the column (plate 11). Figure 2 shows MUD for this base case.



Light Component



Heavy Component

Figure 2. MUD over the whole column, *N*=21, *Fp*= 11 and R_{opt}= 3.0

From the separation performance view of point, we may find that composition of distillate, $x_{1,D}$ and that of the gas from plate 2, $y_{1,2,out}$ has the same value, $x_{1,D}$=0.878 as shown in top-left and top- right side of ordinates in (a). Coversely, it appears in the lower of the figure for heavy component in (b). The composition of gas at equilibrium condition also can be seen at right side of ordinate in (a) and (b). Then composition of gas and liquid for light (a) and heavy (b) components on each plates can be seen clearly on the MUD in Figure 2. Meanwhile, the composition of the feed flowrate can be seen as dash line on the left side of ordinate in (a) and (b), in this case $x_{1,F} = x_{2,F} = 0.5$.

The exergy loss of mixing in liquid phase for light component 1 is displayed on the area of the rectangle for each plate *k* between horizontal line k_{in} and k_{out}. There is only one in the rectifying section (plate 2 through 10) and three section for stripping section (plate 11 through 20). The first and second section shows that the feed is introduced at the saturated liquid, so it will go down and is mixed with the liquid coming from the above feed plate. The first one of the these section indicates that the extent of component 1 corresponding to the width of this part will be discharged as bottoms. The second one shows that this extent of the light component descends first to the bottom, evaporates in the reboiler, rises through the whole column, and leaves the column at top of the column as the distillate. This extent can be seen at the second section of gas phase, while the first section of gas phase condenses in the condenser and circulate in the liquid phase. In this circulation section shows that some part of the light component 1 evaporates at plate 2 through 20, shown by fraction of γ_1, and some part circulates in the column. For the gas phase, there is exergy gain of mixing for component 1 that is given as rectangle for each plate k between horizontal line k_{in} and k_{out} on the right-side of the ordinate in Figure 2 (a).

The flowrate of light componen 1 in the liquid phase decreases with the plate number increased, as shown in Figure 2 (a). The decreases fraction is the fraction γ_1 that evaporates and goes to the gas phase. The smallest of γ_1 appears at the middle of the column. In the gas phase all the light component condenses in the condenser. The driving force for evaporation, given as height **eh** in Figure 1, increases with plate number increased. Consequently the exergy loss of evaporation, given by area of fraction γ_1 and the driving force of evaporation, increases too with the plate number increased. The total exergy loss of evaporation is 67.73 kJ/s.

MUD for heavy component in Figure 2 (b) displays the reboiler at the upper part of the figure. The exergy gain of mixing in liquid phase and exergy loss of mixing in the gas phase are given by a rectangle for each plate k between horizontal line k_{in} and k_{out} on the left-side and right-side of the ordinate in (b), respectively. Then, the difference between the exergy loss of mixing in the liquid phase of light component 1 and that of heavy component 2, resulting in the net exergy loss of mixing in the liquid phase, further we denoted as the exergy loss of mixing in liquid phase. On the contrary, the difference between the exergy loss of mixing in the gas phase of heavy component 2 and that of light component 1, resulting in the net exergy loss of mixing in the gas phase, further we denoted as the exergy loss of mixing in gas phase. These exergy loss of mixing in the liquid and gas phases are 43.99 and 42.17 kJ/s, respectively. The driving force of condensation increases with the plate number decreased. Then the total of exergy loss of condensation, given by area of fraction γ_2 and the driving force of condensation, is 64.71 kJ/s.

By assuming that the heat supplied to reboiler at 5 ^{0}C above the bottom temperature and the heat removed from condenser at 5 ^{0}C below the distillate temperature, resulting in the exergy loss of heating in the reboiler and that of cooling in the condenser are 75.39 and 65.61 kJ/s, respectively. Then, the total of exergy loss is the summation of the exergy loss of sub processes, losses of heating in reboiler and losses of cooling in the condenser, EXL_{total}= 361.19 kJ/s.

Optimum reflux ratio on distillation column

In the base case, we operates the column at reflux ratio, R= 3.0 yielding $x_{1,D}$=0.878 and EXL_{total}= 361.19 kJ/s. Decreasing this reflux ratio to the lowest one, R_{min}= 0.5 resulting in the decreasing separation performance and total exergy loss become $x_{1,D}$=0.7731 and EXL_{total}= 96.21 kJ/s, respectively. On the contrary, increasing reflux ratio from R=3.0 to R= 5.0, for example, gives the increase in total exergy loss become as much as 579.84 kJ/mol, but that increase gives the decreasing separation performance to $x_{1,D}$= 0.8709. In other words, we may say that increasing reflux ratio from the lowest one, it ultimately will reach the condition where the mole fraction $x_{1,D}$ has the biggest possible value. We identify this state as the optimal reflux ratio and R_{opt}= 3.0 is the optimal one for the column considered. This condition corresponds to the average reflux ratio that is located between minimum and total reflux ratios at McCabe-Thiele diagram.

REVAMPING FOR INCREASING SEPARATION PERFORMANCE

There are many reasons to revamp a distillation column. These include increased purities, increased recoveries, decreased environmental impacts and increased capacity. By using the proven strategy to find the most-cost-effective option, revamping an existing plant can improve most existing columns and provides one of the most economically attractive opportunities available in process engineering today. A simple revamp strategy separately addresses each equipment item that limits capacity, and modifies or replaces them by larger. A more careful analysis of the existing column may give insight on alternate revamping strategies that will lead to an optimum design (Barletta, 1998).

Additional more tray

One possibilities of revamping of distillation column is adding more trays, but according to Mix, et al, (1978), tray changes are economically possible if:

$$N^2-\xi^2\frac{\ln\alpha}{\ln s}\sqrt{\frac{PR}{R-1}}<150$$

where N is number of trays in the column, ξ is Murphie plate efficiency, α is relative volatility, P is column pressure (atm) and R is reflux ratio.

Table 1 shows the profiles of separation performance, reflux ratio, reboiler & condenser duties and exergy loss at different plate number. The exergy loss of subprocesses is summation of exergy loss due to phase change (exergy losses due to evaporation and condensation), exergy loss due to mixing and exergy loss due to change in temperature (exergy losses due to heating and cooling).

The exergy loss of evaporation of light component and condensation of heavy component in the phase change are obtained based on the concept of individual energy level. The exergy losses due to heating and mixing in liquid phase as well as the losses due to cooling and mixing in vapor phase are calculated based on the premixing concept as discussed in the previous paper (Budiman and Ishida, 2004). In this concept, vapor flow entering a plate is mixed with an abundant amount of the stream of which composition, temperature and pressure are the same as that of leaving a plate stream. A similar premixing process also is also assumed for liquid stream.

Table 1. Profiles of Separation Performance, Reboiler & Condenser Duties and Total Exergy Loss at Different Plate Number

N	x_{1D}	R	$Q_{reboiler}$ kJ/s	$Q_{condenser}$ kJ/s	Exergy loss, kJ/s			
					subproc	condenser	reboiler	total
11	0.7758	2	4626.83	4603.61	127.82	51.27	57.16	236.25
21	0.8780	3	6035.21	5992.41	220.19	65.61	75.39	361.19
31	0.9354	3.7	6688.78	6637.64	270.60	71.91	84.10	426.61
41	0.9671	4	7368.79	7306.65	316.87	78.71	92.94	488.52

Table 2. Profiles of Separation Performance, Reboiler & Condenser Duties and Total Exergy Loss at Different Column Diameter

D, m	$x_{1,D}$	R	$Q_{reboiler}$ kJ/s	$Q_{condenser}$ kJ/s	Exergy loss, kJ/s			
					subproc	condenser	reboiler	total
0.50	0.8318	3	5337.86	5303.37	171.87	58.54	66.33	296.75
1.00	0.8780	3	6035.21	5992.41	220.19	65.61	75.39	361.19
1.50	0.9325	3.2	6253.02	6200.16	247.79	78.53	67.26	393.58
2.00	0.9556	3.5	6682.37	6598.63	278.42	83.82	71.55	433.79

The exergy loss of cooling in the condenser is calculated by assuming a heat sink at the bubble-point temperature of the distillate. On the other hand, the exergy loss of heating in the reboiler is calculated by assuming a heat source at the dew-point temperature of the bottoms.

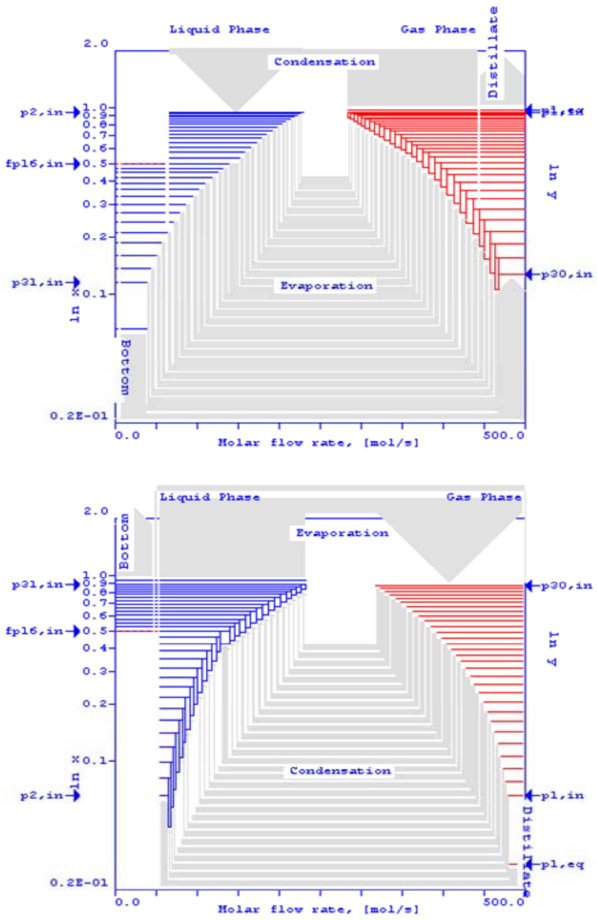
When we look at Table 1, we may find that increase number of tray from N=11 to 41, will increase separation performance, x_{1D} as well as increase reboiler & condenser duties, exergy loss of subprocesses and total exergy loss. This condition is caused by the fact that increase number of tray will increase optimal reflux ratio, *i.e.*, R_{opt}= 3.0 (for N= 21) to R_{opt}= 3.7 (for N= 31).

Figures 3 shows MUD when number of tray is to be N= 31 with F_p= 16 and R= 3.7. Comparison to the base case of N= 21 implies that distribution of both liquid and gas flow rates of light and heavy components has the similar characters, *i.e.*, the distribution of light component decreases from top to the bottom plate and conversely it decreases from bottom to the top plate for heavy component. The distinguished of the two cases is that molar flowrate on a tray at the same plate is increased by increasing number of tray because of increased in optimal reflux ratio. Total exergy loss is 426.61 kJ/s for N= 31, while it is 361.19 for N= 21.

Changing column diameter

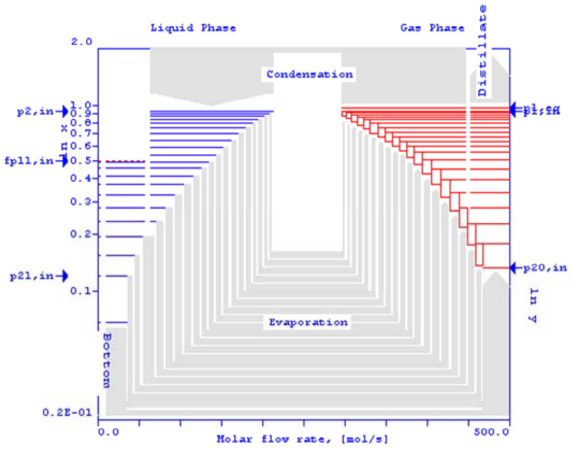
The sieve tray is a low cost device and consists of perforated plate that usually has holes, a down comer, and an outlet weir. Degree of separation depends on process condition, tray spacing and allowable pressure drop. It also is possible to increase separation performance by increasing contact area between gas and liquid. This is particularly true for changing the column diameter (King, 1971).

Table 2 shows the profiles of separation performance, reflux ratio, reboiler & condenser duties and exergy loss at different column diameter. When we analyze Table 2, we may find that increase column diameter from D_i= 0.5 m to 2.0 m, will increase separation performance, x_{1D} as well as increase reboiler & condenser duties,

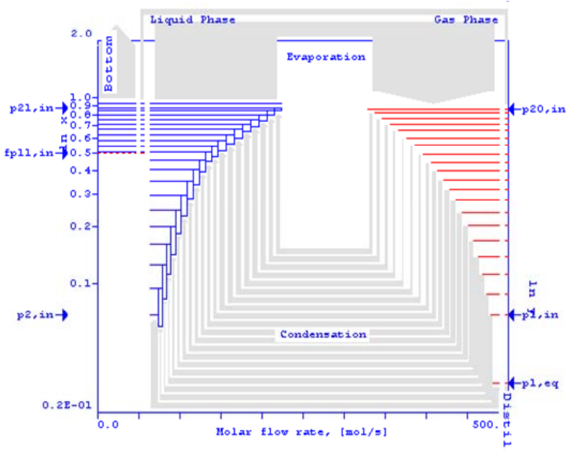


(b). Heavy Component

Figure 3. MUD for N=31, Fp= 16 and R_{opt}= 3.7



(a). Light Component



(b). Heavy Component

Figure 4. MUD for D_i= 2.0 m, R_{opt}= 3.5

exergy loss of subprocesses and total exergy loss. This condition is caused by the fact that increase column diameter will increase optimal reflux ratio, R_{opt}= 3.0 for D_i= 0.5 to R_{opt}= 3.5 for D_i= 2.0 m.

Figures 4 shows MUD for D_i= 2 m with number of holes per plate = 40.000. Comparison to the base case of D_i= 1.0 m in Figures 2, implies that distribution of both liquid and gas flow rates of light and heavy components has also the similar characters, , *i.e.*, the distribution of light component decreases from top to the bottom plate and conversely it decreases from bottom to the top plate for heavy component. Total exergy loss is 433.79kJ/s for D_i= 2.0 m., while it is 361.19 for D_i= 1.0 m..

Installing side heating-side cooling

Another revamping target for energy saving improvement in distillation column is the use of side heating and side cooling (Budiman and Ishida, 1998). The construction of side heating-side cooling can be done by placing coils in the tray of the column to give effect the heat addition or removal. When using this approach for a distillation revamp, the trick is to specify the side heating-side cooling location and fix the heat addition rate that will give maximum overall capacity increase. This is a trial-and-error procedure with no simple formula. Let us examine the use of side heating on plates 16 through 20 and side cooling on plates 2-6 with the heat rate, Q_{sh}= -Q_{sc}= 600 kJ/s.

Figure 5 shows MUD of side heating-side cooling. Comparison to the conventional column in Figure 2, we may find that separation performance increases from $x_{1,D}$= 0.878 for conventional column to $x_{1,D}$= 0.8832. Meanwhile, the net exergy loss of mixing in liquid and gas phases on side heating-side cooling plates reduces significantly. It reduces from 44.0 to 36.52 kJ/s and from 42.18 to 33.53 kJ/s in liquid and gas phases, respectively. For plates without side heating or cooling, *i.e.* plates 7 through 15, fraction ${}_1$ migrates from liquid to gas phases and fraction ${}_2$ migrates from gas to liquid phases. Meaning that light component 1 evaporates and heavy component 2 condenses. These phenomena may happen over the whole column for conventional distillation column. It is important to note that reverse phenomena take place at plates with side heating-side cooling. The light component 1 condenses at plates 2 through 6 against its concentration gradient due to the very strong convective flow in the opposite direction. The exergy loss of condensation resulted from this phenomena is very large. Similarly heavy component 2 evaporates at plates 16-20 against its concentration gradient as the result of the strong convective flow. The fractions ${}_1$ and ${}_2$ at side heating and cooling plates increase, while the driving force of evaporation of light component 1 and that of condensation of heavy component 2 at those plate decrease as compared to the case of conventional column. For this case, the heat supplied to reboiler and removed from condenser decrease significantly from Q_R= 6036.1 to 3478.7 kJ/s and Q_C= 5992.4 to 3441.0 kJ/s, respectively. Total exergy loss is EXL_{total}= 316.5 kJ/s, while for conventional column EXL_{total}= 361.19 kJ/s.

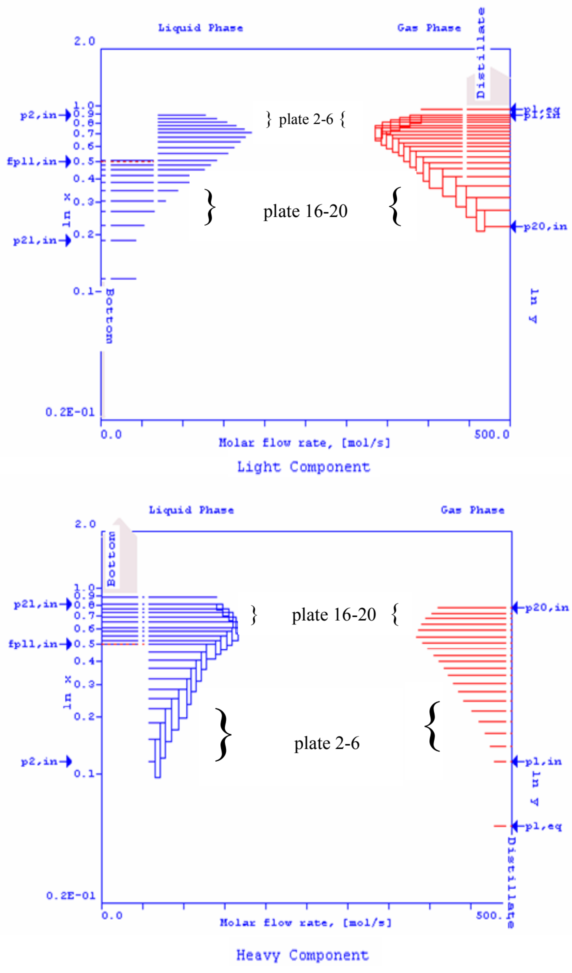


Figure 5. MUD for Side Heating-Cooling, Q_{sh}=-Q_{sc} 600 kJ/sec

CONCLUSIONS

The present work shows that material-exergy analysis based on MUD can display separation performance, transfer of material and exergy characteristics over the whole column compactly. Therefore, MUD methodology can identify the targets for restructuring and modifications, and may be helpful in suggesting for revamping of distillation column. Additional more trays and more wide column diameter improve pure component and increase the net exergy loss. While, the use of side heating-side cooling improves separation performance and reduces the net exergy losses.

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