STUDY OF INTERNAL RECYCLE DISTRIBUTION AND HEAT TRANSFER EFFECT FOR OPTIMAL DESIGN OF DIVIDING WALL DISTILLATION COLUMNS

Kihong Lee*, Moonyong Lee*, Seongoh Jeong**,
*School of Chemical Engineering & Technology, Yeungnam Univ., Kyungsan, Korea
(+82-53-810-3241; Email :kihongi@hitel.net, +82-53-810-2512; Email :mynlee@yu.ac.kr)
**LG Siltron Co., Korea
(+82-016-520-0746; Email : castleo@dreamwiz.com)

Abstract : This paper addresses the optimal design of dividing wall distillation column which is rapidly applied in a variety of chemical processes over recent several years because of its high energy saving efficiency. A general dividing wall column model which can cope with the heat transfer through the dividing wall is developed using rigorous computer simulation. Based on the simulation model, the effects of the internal recycle flow distribution around the dividing wall and the heat transfer across the dividing wall on overall system performance are investigated. An improved method is suggested to utilize the heat transfer through the wall to optimal column design. The suggested method is compared with the existing method via. simulation study and shows more improved energy saving result. Several control strategies for the divided wall column are tested and the optimal control strategy is propose

Keywords : dividing wall column, internal recycle flow, heat transfer effect, energy saving

Ⅰ. Introduction

Distillation processes are the representative separation process that accounts 90% of separation method for the separation of mixture. At the same time, distillation processes are typical energy consumption process because of specific characterization of process[1]. In order to minimize energy consumption of these distillation processes, various try[2,3,4] have been preformed, we can lift the Petlyuk column as a representative example of the approach way that is going to achieve an energy saving from thermally integrated complex distillation structure. However, in spite of the excellent latent energy saving effect, the application in industrial processes of Petlyuk column is extremely restrictive because of a process design and operation problem. The dividing wall column that its application began in middle of 1980's to the industrial world is the most developed structure that have a form of integrated prefractionator of the Petlyuk column in the main column using dividing wall. It is almost thermo- dynamically same as a Petlyuk column, so it gives excellent energy saving effects and have a easy operation because of natural pressure balance between main column and prefractionator and have a great advantage in the side of capital cost because of the integration of columns, so it is rapidly applied in a variety of processes over recent several years[5,6,7].
Internal recycle flowrate distribution and heat transfer

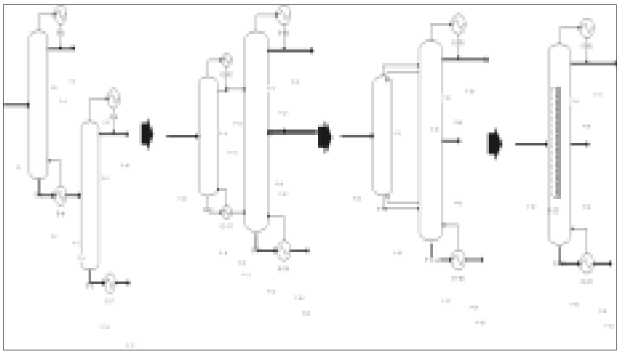

Fig. 1. Distillation process configurations for ternary mixture separation

characteristics through the dividing wall is different from a Petlyuk column and it must be considered while basic design of dividing wall column. Internal recycle flowrate distribution between dividing wall cause serious effect in total separation performance. It is possible to adjust recycle flow distribution between prefractionator and mail column during operation in a manner voluntarily in a Petlyuk column, on the other hand, a case of dividing wall column, it is physically impossible that adjust internal flow distribution during operation in a manner voluntarily if design is over. so, optimal distribution structure must be decided in a design step. Also, a heat transfer can happen between mail column and prefractionator through dividing because of temperature gradient. This heat transfer effect cause energy benefit or loss according to a section. Precision analysis and guideline to a design step are indispensable because heat transfer effects can be important design variable to cause an influence to be important for column total performance.

The main issue of This paper are rigorous computer simulation by these dividing wall column and analysis of internal recycle flow distribution, heat transfer characterization between wall, and researches the effect that cause the optimum design.

2. Modeling of Dividing wall column

Dividing wall distillation column is thermodynamically equivalent with Petlyuk distillation column except the heat transfer through the dividing wall. Therefore, the most general model of dividing wall column model was implemented that includes heat transfer effect through the dividing wall by installing virtual heat exchangers between each stage of prefractionator and mail column as shown figure 2. Degree of freedom analysis of dividing wall column was done for find a solution of composed model. In the case of dividing wall column, Number of stages and pressure of prefractionator and main column, feed inlet stage, temperature, pressure, and composition of feed stream are fixed, then the degree of freedom is 5. Additionally, 2 degree of freedom remains after fixing the purity of overhead, side, bottom products. It means there are infinite operation condition in dividing wall column to satisfy given product specification, and we can use appropriately these remaining two degrees of freedom as a

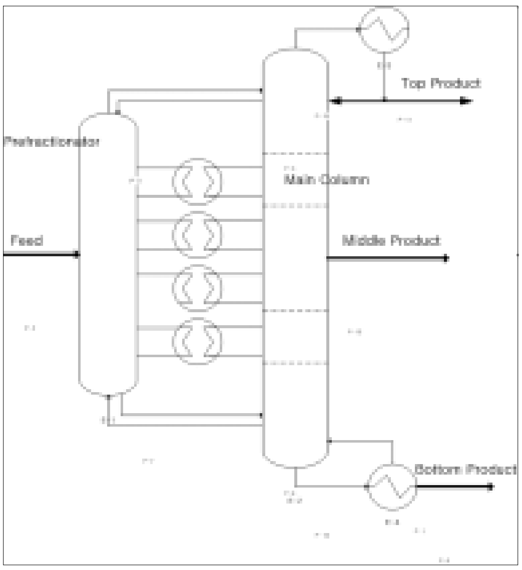

Figure 2. The conceptual design of dividing wall column

optimized design variables to maximize energy savings.

The HYSYS™ simulator of Hyprotech was used to the model implementation. By choosing liquid and vapor internal recycle flowrate tat flows from main column to prefractionator as a cutting point of iterating calculation for solve total process, solution of total system can be converged stably. Simulation study implemented with three component mixture that contains methanol-isopropanol-butanol used by Lestak[8]. Basic conditions shown in table 1. Feed inlet stage calculated 30th stage by optimization. UNIQUAC equation was used for Vapor-Liquid equilibrium calculation.

Table 1. Base operation condition used in simulation study

Feed composition	methanol	200 kgmol/h
	iso-propanol	500 kgmol/h
	butanol	300 kgmol/h
Feed condition	saturated liquid, 1.15 bar	
Number of tray	prefractionator 38 ; main column 70 (reboiler and condenser are excepted.)	
Specification of products	The purity of primary component at each products is 95 mol% each.	

3. Effect of Internal Recycle flow distribution

In the dividing wall distillation column, the internal recycle flowrate that flows prefractionator and main separator through dividing wall is one of the most effective design variable that cause overall system separation performance and energy consumption. In this paper, we select the optimization variable that vapor and liquid internal recycle flowrate, and analyzed quantitative/ qualitative effect and reason that influences of the internal recycle flowrate through simulation study. Internal recycle flowrate to the prefractionator is applicable that internal reflux rate and reboiled rate in general distillation column, and it determine the separation performance in prefractionator. Such change of separation performance in prefractionator brings the change of internal recycle flowrate in main separator for satisfy given product purity.

Figure 3 shows total required energy in the condenser and reboiler according to vapor and liquid internal recycle flowrate to the prefractionator when required purity of final products are fixed. In this simulation study, we assumed that dividing wall is perfectly insulated, so there are no heat transfer through dividing wall. figure 3 shows optimal internal recycle flowrate exists explicitly that minimizes total energy requirement and total energy requirements is taking proper influences according to the internal recycle flowrates. In the case of this simulation study, the lowest energy requirement is 12.06×10^{7} KJ/h when internal recycle flowrate of vapor and liquid are 900 kgmol/h and 500 kmol/h respectively. On the other hand, the highest energy requirement in the searching area is 58.52×10^{7} KJ/h, so there are very big change width of total energy requirements.

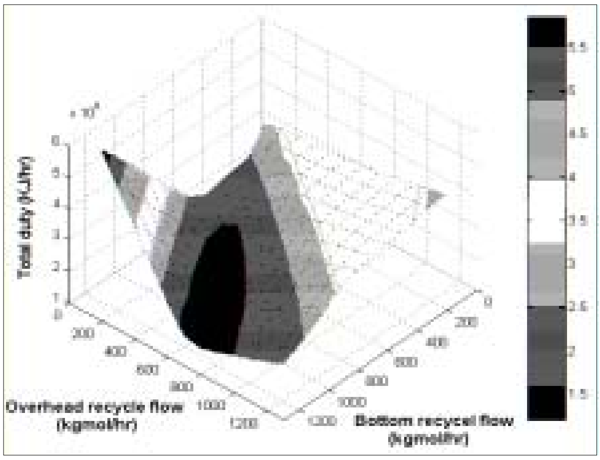

Fig. 3. Total required energy for separation according to vapor and liquid internal recycle flow rate

For the explanation of optimal operation condition according to the relative ratio of internal recycle flowrate, we fixed the liquid internal recycle flowrate to 500 kgmol/hr. The purity change of products of the prefractionator according to the change of vapor internal recycle flowrate was looked. The results shows in figure 4. As shown in figure 4, when vapor internal recycle flowrate relatively lacks compared to liquid internal recycle flowrate, then most of lightkey component discharges into the bottom product because of an energy shortage for separation cause a bit stripping of lightkey component in the liquid internal recycle flowrate, so the purity of heavykey component in the prefractionator becomes low. On the other hand, low separation efficiency causes the discharge of heavykey component into the top product of prefractionator, so the purity of lightkey component at the top product becomes low. Finally, insufficient separation of prefractionator makes to increase the load of separation and this means higher internal recycle flowrate(it means higher energy consumption). If vapor internal recycle flowrate increase suitable level, the stripping of lightkey component in the liquid internal recycle flowrate is increased, and the purity of lightkey component in the top product and the purity of heavykey component in the bottom product of prefractionator are increased. A separation performance of prefractionator which is increased in this way brings a degrade of separation energy of the main column. On the other hands, vapor internal recycle flowrate relatively too much, then the lightkey components in liquid internal recycle flowrates are whole stripped and be saturated condition, but stripping performance of vapor internal recycle flow rapidly decrease, so much of heavykey component goes up to the top product. Accordingly, the purity of lightkey component in the top product and heavykey product in the bottom become lowly so that separation load increase in the main column for the satisfaction of the given purity of products. As shown in figure 3, the vapor internal recycle flowrate that minimizes energy load is about 900 kgmol/h when liquid internal recycle flowrate is 500 kgmol/h. This flowrate condition almost same the condition that the separation is achieved best in prefractionator as shown in figure 4.

In the mean time, looking for the trajectory of vapor and liquid internal recycle flow, then total energy requirements decreases by the increase of total internal recycle flowrate. But if total flowrate is grown more than any value, the increase of total energy requirement can be saw. Existence of these optimum point can be explained as following. The increase of vapor and liquid internal recycle flowrate of prefractionator effects the improvement of separation performance of prefractionator, so it causes

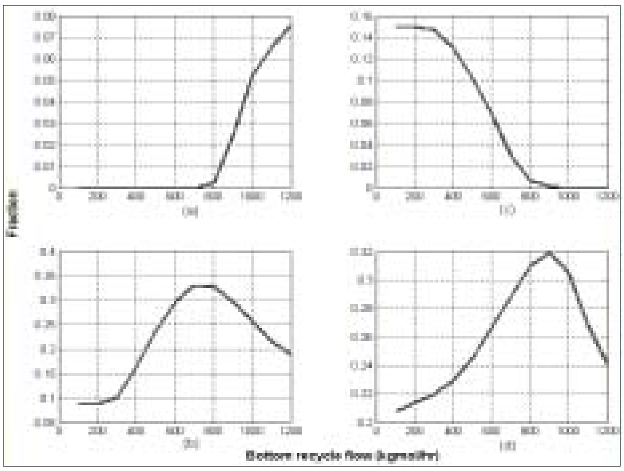

Fig. 4. Purity of prefractionator products according to vapor internal recycle flow
(a) heavy key component in top product, (b) light key component in top product, (c) light key component in bottom product, (d) heavy key component in bottom product

the effect that the decrease of internal reflux rate of main column. But the other side, it can have a effect of increase of separation load because of the increase of internal recycle flowrate induces the increase of internal recycle flowrate of main column directly. Because these two effects happen each other competitively, while when internal recycle flowrate increases, separation performance elevation effect by recycle flowrate increasing is superior to some condition. After this condition, effect that increase internal recycle flowrate of main column becomes superior and optimal point by total flowrate of internal recycle flow is appeared finally.

4. Effect of Heat transfer through dividing wall

One of the major differences of the dividing wall column and Petlyuk column is the possibility of horizontal heat transfer caused by temperature differences through the dividing wall between prefractionator and main column. These heat transfer effect causes beneficial effect and non-beneficial effect all to the overall performance of dividing wall column. Paying attention to such fact, Lestak[8] suggested method that divide beneficial area into non-beneficial area centering into pinch point of main column and applicate this to design of dividing wall column. But this method contains the vagueness of area divination and analytical problem of heat pocket.

For example, in the case of this simulation study, grand composite curve and temperature distribution of dividing wall column shows at figure 5. Y-axis of the figure represents stage number that puts sequence from bottom to top and stage number of prefractionator marked the applicable stage number of main column. As shown in figure 5, in the case of main column, centering around the pinch point that 40th stage, upper part is a heat receiving area from hot utility, and lower part is a heat donating area to cold utility. On the other hands, in the case of prefractionator, it is most desirable that upper part receives heat and lower part donates heat centering around the 17th stage of main column. But if looking into the temperature distribution then temperature of prefractionator is lower than temperature of main column, so heat flows from main column to prefractionator naturally except for perfect insulation of heat.

As shown in figure 5, 17th~40th stage of main column is a area that main column have to discharge heat, and heat flows from main column to prefractionator naturally through the dividing wall. So this area can be classified to beneficial area that can achieve energy reduction when

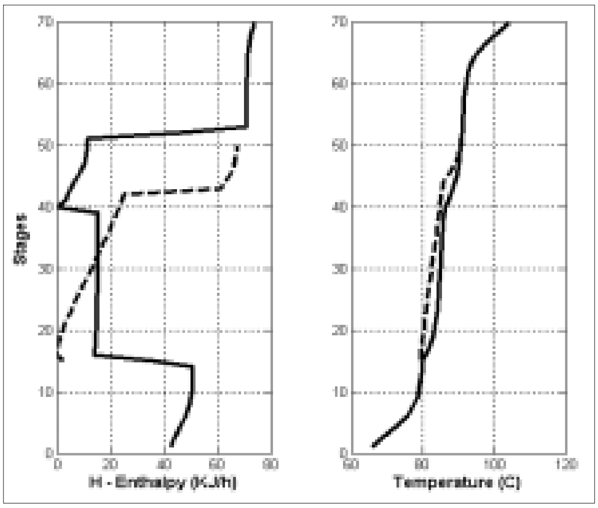

Fig. 5. Grand composite curve and temperature distribution curve of prefractionator and main parts

heat transfer through dividing wall permitted. On the hand, 40th~50th stage of main column is a area that have to receive heat, but heat flows from main column to prefractionator. So this area could be analysis for non-beneficial area that heat transfer is not desirable. Contradictory conclusion appears here, there is possible analysis that the heat transfer in the area that 40th~50th stage of main column is heat receiving area for prefractionator and permitted actively because of looking into at the viewpoint of prefractionator, it is beneficial area that heat transfer is desirable. The area Below the 17th stage has dubious area division because of resemblant reason. Therefore, in this case, it is impossible that sort two areas by grand composition curve and temperature distribution information as proposed method by Lestak[8]

Also, Lestak's proposed area division method that centering around pinch point must be prerequisite that self heat recovery is available for parts that appear in form of heat pocket in grand composite curve. But, our consideration in dividing wall column is just heat transfer through dividing wall therefore heat recovery of heat pocket area are excluded naturally.

To improve problems of these existing method, we suggest some method in this paper that (1)divide dividing wall into heat supplying area and heat disappearing area based on slope information of enthalpy at each separator, (2)based on (1), divide into heat transfer beneficial area and non-beneficial area at the viewpoint of main column and prefractionator all. For example, consider the 39~40th stage of main column. enthalpy slope of grand composite curve is negative at main column therefore it is heat supplier, and enthalpy slope is positive at prefractionator therefore it is heat disappearer. In the mean time, looking for the temperature distribution table, heat flows from prefractionator to prefractionator. Therefore, this area is fallen into definite beneficial area. Also, the area that 15th~16th of main column can classify non-beneficial area for resemblant reason. While areas corresponding that 17~39th and 40~40th stage of main column are heat disappearer both main column and prefractionator, but heat flows from main column to prefractionator, there we can't make conclusion for beneficial or non-beneficial area. Therefore, all of possible cases must be compared about this section and confirm case that need minimum energy by trial and error.

Table 2 shows the results that compared Lestak's method with proposed optimal area division in this paper and energy consumption at each method. Heat transfer coefficient was fixed 20,000 W/℃ at the dividing wall. As shown in table 2, it is more efficient by partial heat-insulating than whole-insulating of dividing wall. Specially proposed method in this paper offers smallest energy consumption.

Table 2. Classification of benefit and non-benefit areas in dividing wall and corresponding energy consumption

	whole-insulating	Lestak's method	proposed method
area division	NB	NB B	B B B NB
Energy requirement ($\times 10^7$ KJ/hr)	12.09	12.03	11.87

In the meantime, it may become main private issue that must solve for an actual application of optimal design of dividing when practical manufacturing of dividing wall

5. Effect of Heat transfer coefficient

If heat transfer rate of dividing wall can be randomly adjusted, heat transfer coefficient can be important optimizing design variable. The heat transfer through dividing wall of each stage can be represented as shown in the below.

$$q = UA\triangle T \quad (1)$$

In this equation, q represents the heat transfer rate through dividing wall, U is the overall heat transfer coefficient, A is the Area of dividing wall, and T is a temperature differences between wall.

To look the effect that the change of the heat transfer coefficient influences on the total requirement energy, the internal recycle flowrate of liquid and vapor was fixed to 500kgmol/h and 900 kgmol/h respectively, and UA was varied to 100~30,000W/℃. The result of computer simulation was shown in figure 6.

As shown in figure, there can be exist optimal heat transfer coefficient. In the case of this simulation research, the difference between perfectly heat insulated dividing wall and the case that designed by optimal heat transfer coefficient is approximately 2.0×10^6 KJ/hr. It is relatively small influence compared to the internal recycle flowrate.

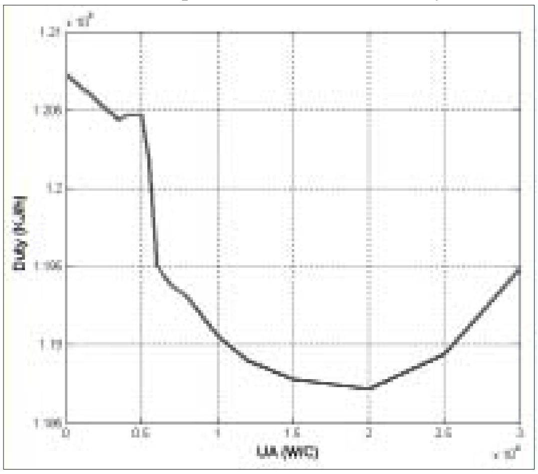

Fig. 6. Effect of UA on energy consumption

6. Effect of feed inlet tray

The design procedure of general distillation tower determines the number of stage first, and fix the feed inlet tray by shortcut method, and accomplish optimal design for another variables. Similarly, in the case of dividing wall distillation column, fixes feed inlet stage by using the fixing method of feed inlet tray of general distillation column, and accomplish the optimal design for another variables. But, when the feed inlet tray was determined based on the prefractionator ,there are many chances to escape overall optimal point because of prefractionator and main separator of dividing wall column combined each other to the compositeness. Some simulation study were accomplished for the effect of feed inlet stage to the energy efficiency of dividing wall column. Figure 7 shows the variety of the energy consumption rate by the change of feed inlet stage. At these simulations, dividing wall fixed to whole heat-insulated, but internal recycle flowrates are applied by optimal value at each feed inlet tray condition.

In this simulation study, the feed inlet tray by existing method[9] is 23th stage. On the other hand, optimal feed inlet stage by optimization is 30th stage, so it shows the difference not to ignored by comparing to the result of shortcut method. But in the case of this simulation study, as shown in figure 7, total energy consumption rate does not changing very greatly about the change of wide range compared to cases of another design variables. This shows the feed inlet stage that a little escaped from optimal value can be maintained in the range to satisfied overall performance by appropriately designed internal recycle flowrate.

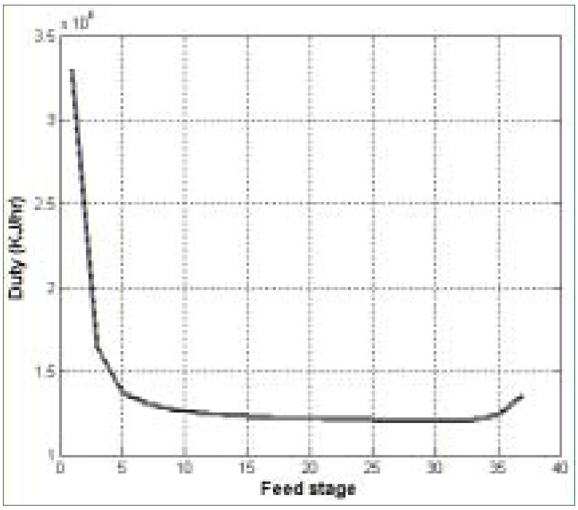

Fig. 7. Minimum required energy *vs.* feed inlet tray change

Ⅶ. Conclusion

The effect of main design variables to the energy consumption was analyzed for the optimal design of dividing wall column using rigorous computer simulation. As a result, the internal recycle flow distribution between dividing wall can cause largest effect to the optimal design was identified, and the reason that the existence of optimal value can be explained by relating the separation performance of prefractionator. We confirmed the heat transfer through dividing wall can give much effect to the separation performance of the whole system, and suggested the method that divide the dividing wall area to the beneficial area and the non-beneficial area taking all viewpoint of prefractionator and main column based on the enthalpy slope of grand composite curve for the improvement of problem of existing area dividing method and can identify the effectiveness through the simulation research.

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