

INTERNAL COLUMN-TO-COLUMN HEAT TRANSFER CHARACTERISTICS FOR ENERGY-SAVING DISTILLATION SYSTEM

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An experimental study was performed to observe heat transfer characteristics for design of an internal heat integrated distillation column system. The overall heat transfer coefficient and temperature difference were measured between the higher-pressure rectifying section and the lower-pressure stripping section. It has been confirmed that the pressure ratio between the rectifying and stripping sections, i.e. the compression ratio is the main parameter controlling the degree of heat integration.

KEYWORDS: energy-saving distillation, internal heat integration, plate column, heat transfer, double-tube column

INTRODUCTION

As a possible way for pumping up the energy released from the overhead condenser to the reboiler, the pressure of the rectifying section with the overhead condenser should be raised by a compressor, as shown in Figure 1, so as to make the boiling point higher than that of the stripping section with the reboiler. This is one of the internal heat integrated distillation column (HIDiC) systems which reduce greatly the heat duties of the reboiler and condenser (Nakaiwa et al. 2003). The present study deals with double-tube type, two coaxial cylindrical distillation columns equipped with dual flow trays (named Lift Tray), the inner one of which serves as the pressurized (higher-temperature) rectifying section and the outer one, i.e. the annular column serves as the normal pressure (lower-temperature) stripping section. (see Figure 2).

EXPERIMENT

The double-tube distillation column shown in Figure 2 has an inner column of 508 mm ID and an outer annular column of 800 mm ID. The stage-to-stage spacing of each column is 400 mm but the trays of the outer column were arrayed in a staggered line with the trays of the inner column. The outside heat transfer interface was made effectively wet with the liquid film falling from the upper tray.

Only for observation of internal heat transfer characteristics, each column had its own condenser and reboiler. The outer column (assumed as the stripping section) was operated at normal pressure ($P_s = 1$ atm) whereas the operation pressure (P_r atm) of the inner one (assumed as the rectifying section) was changed without compressor (Noda et al. 2004). In relation with the compression ratio of the HIDiC system with

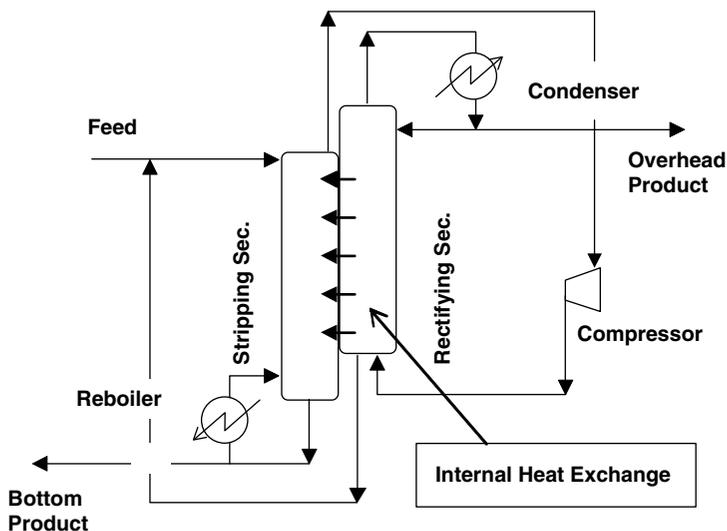


Figure 1. Configuration of heat integrated distillation column (HIDiC)

compressor, the pressure ratio P_r/P_s can be regarded as the main control parameter. The two columns were independently operated in the total reflux condition. Figure 3 indicates that additional condensation in the rectifying section causes additional vaporization in the stripping section.

Heat transfer characteristics were observed in between the rectifying and stripping sections operated with a binary mixture of benzene and toluene. Under the total reflux condition with the specified pressure of the inner column, the following data of each column were obtained: flow rates and temperature of external reflux and bottom liquid flow; temperatures of top and bottom vapor flow leaving and entering the column; temperature and concentration of vapor over each stage.

The following enthalpy balance was calculated using the experimental data to determine the heat exchange rate:

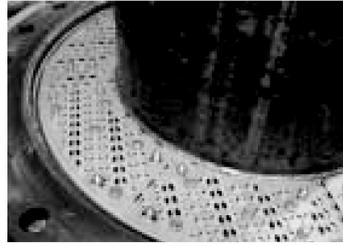
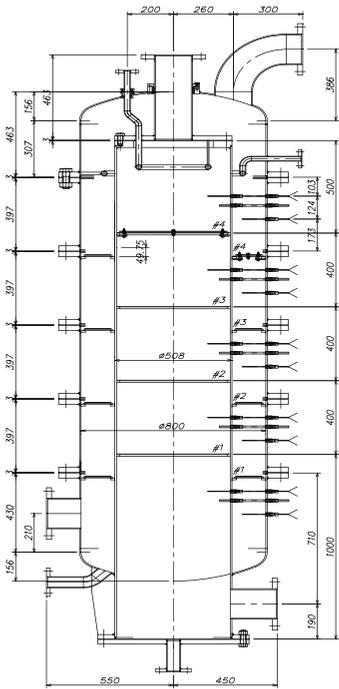
Inner column:

$$Q = L_{tr} HL_{tr} + V_{br} HV_{br} - L_{br} HL_{br} - V_{tr} HV_{tr}$$

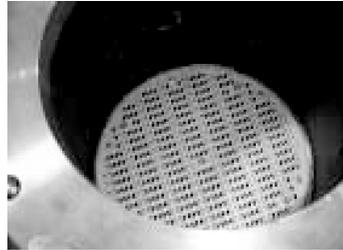
Outer column:

$$Q_{loss} = Q + L_{ts} HL_{ts} + V_{bs} HV_{bs} - L_{bs} HL_{bs} - V_{ts} HV_{ts}$$

Here Q = heat transfer rate (W), Q_{loss} = external heat loss from the outer column (W), L and V = flow rate of liquid and vapor (mol/s), HL and HV = enthalpy of liquid and vapor



Stripping Section Tray (Annular Space)



Rectifying Section Tray (Cylindrical Space)

Figure 2. Double-tube type HIDiC distillation column (4 stages) and dual flow trays used for the rectifying and stripping sections

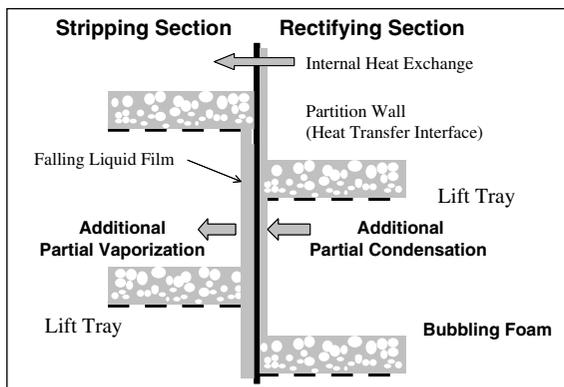


Figure 3. Schematic picture of internal heat exchange mechanism

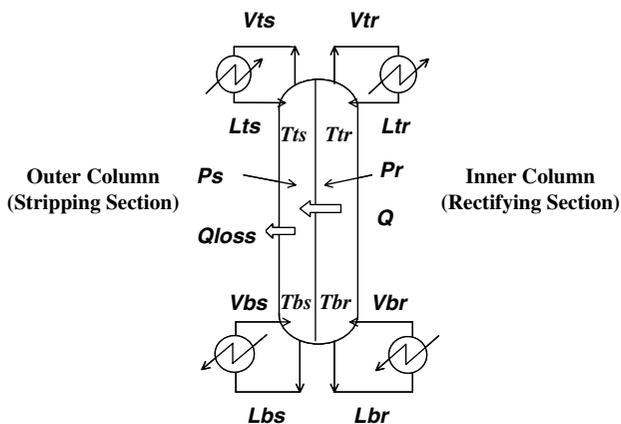


Figure 4. Enthalpy balance set up in two columns operated independently under total reflux condition

(J/mole), and the subscripts t and b = top and bottom, r and s = rectifying and stripping section. Figure 4 shows a schematic picture for explanation of the enthalpy balance of the two columns operated independently under the total reflux condition.

The overall heat transfer coefficient was defined as

$$U = \frac{Q}{A \text{ LMTD}}$$

Here the logarithmic mean temperature difference LMTD was defined with the vapor temperature differences between the two columns measured at the top and bottom.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 5 shows the stagewise variation of temperature and vapor concentration (benzene mole fraction) in the outer and inner columns. In order that the present system might attain the same concentration variation as the typical HiDiC configuration shown in Figure 1, toluene-rich and benzene-rich solutions were respectively supplied into the outer-column and inner-column reboilers. As a result, the top of the outer column (ys at stage #0) should have been coincided in vapor concentration with the bottom of the inner column (yr at stage #5) but there appears some small discrepancy between them. This can be conjectured to be due to the additional concentration occurring in both the columns owing to the partial condensation and vaporization. This did not, however, lead to a large effect on the heat transfer analysis.

Figure 6 shows variation of internal heat exchange (heat transfer rate) with the pressure ratio Pr/Ps . This clearly indicates one of the typical HiDiC characteristics that

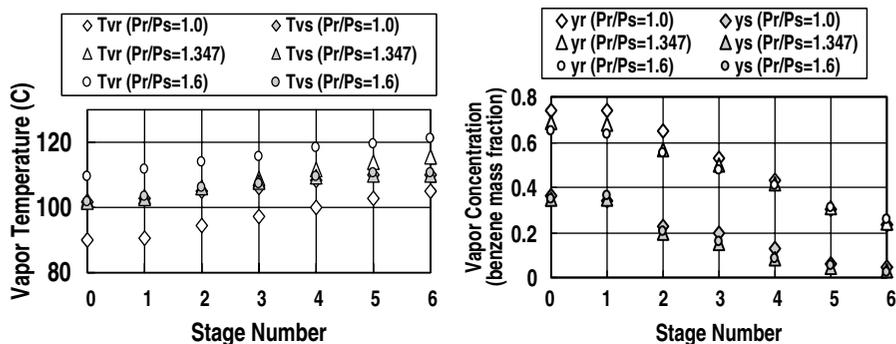


Figure 5. Stagewise variation of vapor temperature and concentration. Stage #0 = top, #5 = bottom, #6 = reboiler

the internal heat integration is directly proportional to Pr/Ps , i.e. the compression ratio. If the inner column is also operated at normal pressure, i.e. Pr equal to Ps for the binary system of benzene and toluene, the heat transfer occurs in the reverse direction, i.e. from the outer to the inner column because the concentration of less-volatile component is larger in the outer column (stripping section) than in the inner column (rectifying section).

Figure 6 indicates that the HIDiC condition can be attained when the compression ratio goes beyond 1.25. The same figure also shows a result of the extra experiment conducted by supplying pure toluene only into the both columns. It has been ascertained that the heat transfer rate becomes zero for the pure toluene case when the two columns are operated at the same pressure, i.e. $Pr/Ps = 1$.

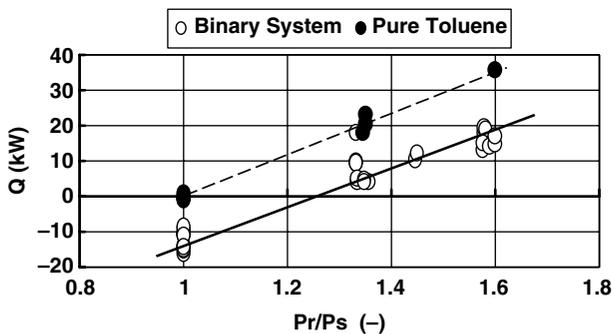


Figure 6. Variation of heat transfer rate with pressure ratio

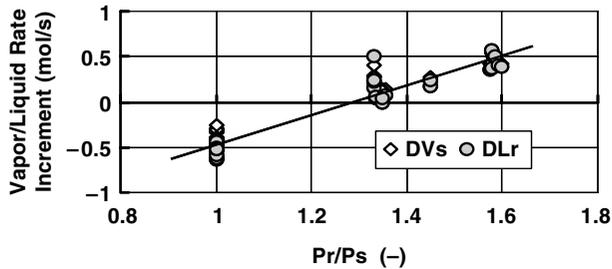


Figure 7. Variation of vapor and liquid flow rate increments with pressure ratio. DVs: Increment of vapor flow rate in the stripping section, DLr: Increment of liquid flow rate in the rectifying section

As mentioned in Figure 3, the energy released due to the partial condensation of vapor in the inner column (rectifying section) causes the partial vaporization of the internal reflux liquid in the outer column (stripping section). Figure 7 indicates that the increment of the internal reflux liquid of the inner column regarded as the degree of internal heat integration is linearly proportional to the pressure ratio. It has also been found that the increment of the stripping section vapor is equal to that of the rectifying section liquid owing to the almost equal molar heats of vaporization of the two components.

As shown in Figure 8, the overall heat transfer coefficient remains almost constant between 500 and 1000 W/m²K in the range of HIDiC condition (Pr/Ps > 1.25). This is due to the fact that the mechanism for the partial condensation and vaporization does not change remarkably with pressure. It is a reasonable result that the coefficient of the binary system becomes about half as large as that of pure toluene case owing to

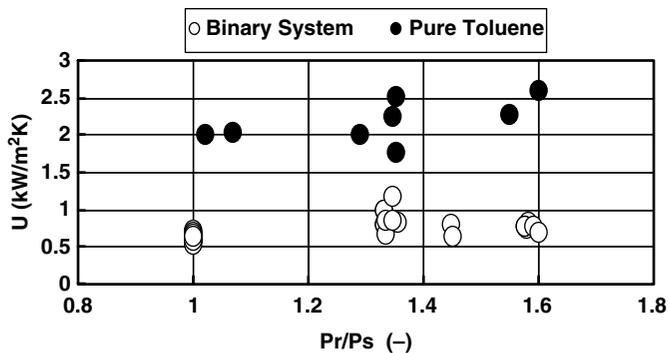


Figure 8. Correlation of overall heat transfer coefficient with pressure ratio

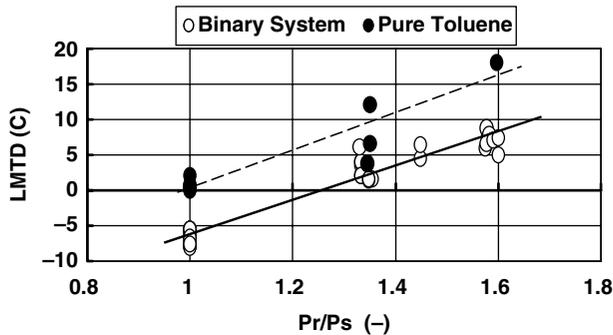


Figure 9. Variation of logarithmic mean temperature difference with pressure ratio

mass transfer resistance in the vapor film on the heat transfer interface. The overall coefficient U cannot be determined for the pure toluene case when $Pr/Ps = 1$.

Figure 9 shows variation of the logarithmic mean temperature difference with pressure ratio.

It has been confirmed that the temperature difference is linearly proportional to the pressure ratio because of the boiling point of the inner column solution rising with the operation pressure. This implies that the most important parameter controlling the internal heat integration must be the compression ratio.

Figure 10 shows whether or not the vapor flow rate influences on the heat transfer coefficient, where the F-factor is averaged between the top and bottom of each column. As can be seen from Figure 10, the overall heat transfer coefficient does not change so much

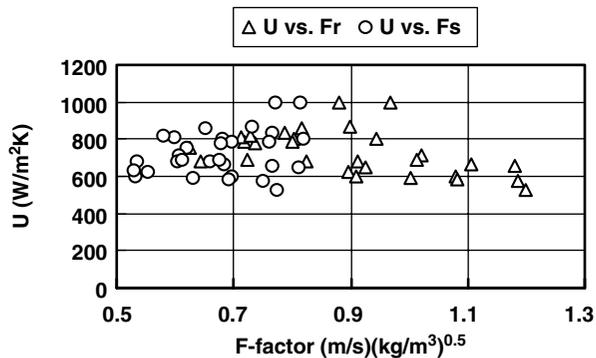


Figure 10. Effect of vapor flow rate on overall heat transfer coefficient. Fr: F-factor of the inner column, Fs: F-factor of the outer column

either with the F-factor of the inner column F_r or with the F-factor of the outer column F_s because the heat transfer is mainly controlled by phase transformation occurring at the interface between the two columns.

CONCLUSION

Internal heat integration due to the heat transfer from the rectifying to stripping section is predominantly controlled by partial condensation of vapor flow in the rectifying section inducing partial vaporization of internal reflux liquid in the stripping section.

The following results of practically – important heat transfer characteristics necessary for the design of internal structure for heat transfer and operation of the HiDiC systems were obtained.

- (1) The heat transfer rate increases linearly with the compression ratio.
- (2) The increment of the internal reflux liquid of the rectifying section regarded as the degree of internal heat integration is linearly proportional to the compression ratio.
- (3) The overall heat transfer coefficient is controlled predominantly by phase transformation heat transfer and remains almost constant between 500 and 1000 W/m²K in the range of HiDiC condition ($P_r/P_s > 1.25$).
- (4) The logarithmic mean temperature difference increases linearly with the compression ratio because of the rise in boiling point of the rectifying section with pressure.

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