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Study on a Continuous Heat Integrated Distillation Column

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Abstract

A novel continuous heat integrated distillation column called a concentric column has been studied using computer simulation. It is shown that a concentric column is a novel implementation of a thermodynamically reversible distillation column and has a lower energy loss than an ordinary distillation column. Our studies show that a concentric column has reduced column height, since the stripping section is configured concentrically around the rectifying section, and uses less utilities than a conventional column.

INTRODUCTION

Heat integration methods in distillation column systems can be classified into two categories: Intercolumn (heat transfer between different columns) and intracolumn (heat transfer within the same column). In each category the heat transfer can either be direct (via mixing of the streams) or indirect (involving heat transfer surface area). Using this classification, the various heat integration methods are summarized in Table 1.

In this paper a continuous heat integrated distillation column, also referred as a concentric column in Table 1, is studied. A schematic of the column is shown in Fig. 1. It consists of a low pressure stripping section configured concentrically around the high pressure rectifying section,

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TABLE 1
Classification of Various Energy Integration Methods

1. Indirect intercolumn heat transfer
A. Sequential column train heat exchanger networks (*1–8*)
B. Split towers (*9–13*)
2. Direct intercolumn heat transfer
A. Petlyuk's intercolumn refluxing (*8, 14*)
B. Petlyuk's intercolumn reflux streams and combined product columns (*8, 14, 15*)
3. Indirect intracolumn heat transfer
A. Heat pumps, vapor recompression (*7, 10, 11, 16–21*)
B. Intermediate reboilers and condensers (*11, 22*)
C. Secondary reflux and vaporization (*23–25*)
4. Direct intracolumn heat transfer
Concentric column

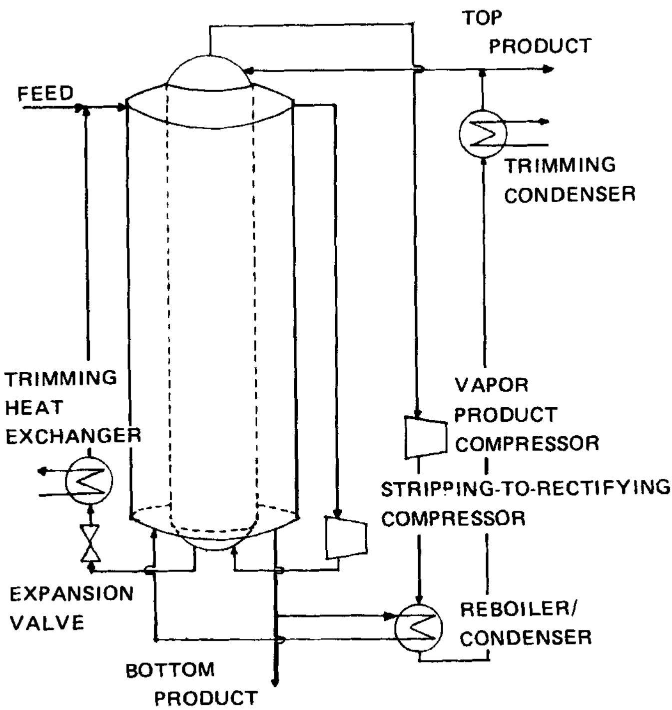

FIG. 1. Schematic of the continuous heat integrated or concentric column.

like a double pipe heat exchanger. Heat from the high pressure (high temperature) rectifying section flows into the low pressure stripping section continuously along the length of the column. A compressor is needed to compress the vapor leaving the top of the stripping section, and a throttling valve reduces the pressure of the liquid leaving the bottom of the rectifying section.

The concentric column design can be utilized for a single column as shown in Fig. 1 or for multicolumn systems as shown in Figs. 2. The hatched sections are the ones which are heat integrated concentrically, and no compressor or throttling valve is needed between the sections. Five possible multicolumn configurations are shown in Figs. 2.

In Fig. 3 a schematic of a possible design for a heat integrated tray in a concentric column is shown. Heat exchange occurs through the common wall between the rectifying and stripping sections. While this design is not investigated in this paper, it is suggested as a possibility for enhancing heat transfer between the two sections and achieving the heat transfer coefficients used in this paper.

THERMODYNAMIC ANALYSIS

Distillation columns have been extensively thermodynamically analyzed in the literature (*19*, *20*, *23–25*). Hence it will suffice to offer a comparison between an ordinary distillation column and a continuous heat integrated column by using energy analysis. The total available energy loss for an ordinary distillation column can be written as

$$\Delta E = \left(1 - \frac{T_0}{T_H}\right)Q_R - \left(1 - \frac{T_0}{T_c}\right)Q_c - FC_F\left(T_F - T_0 - T_0 \ln \frac{T_F}{T_0}\right)$$

$$+ DC_D\left(T_D - T_0 - T_0 \ln \frac{T_D}{T_0}\right) + WC_W\left(T_w - T_0 - T_0 \ln \frac{T_w}{T_0}\right)$$

$$- F\tilde{R}T_0 \sum_{i=1}^{c} X_{Fi} \ln X_{Fi} \tag{1}$$

The first two terms represent the available energy loss of the heat source and sink streams. Under isobaric conditions, the third, fourth, and fifth terms related to sensible heat changes are usually small. The last term represents the minimum available energy required to obtain pure products from a feed mixture at temperature T_0.

The total energy loss in a continuous heat integrated or concentric column can be written as

$$\Delta E' = \left(1 - \frac{T_0}{T_H}\right)Q_R' - \left(1 - \frac{T_0}{T_c}\right)Q_c' + T_0 \int_0^{Q_T}\left(\frac{1}{T_s} - \frac{1}{T_R}\right)dQ$$

$$- Fc_F\left(T_F - T_0 - T_0 \ln \frac{T_F}{T_0}\right) + DC_D\left(T_D - T_0 - T_0 \ln \frac{T_D}{T_0}\right)$$

$$+ WC_W\left(T_W - T_0 - T_0 \ln \frac{T_W}{T_0}\right) - F\tilde{R}T_0 \sum_{i=1}^{c} X_{Fi} \ln X_{Fi} + W_c \quad (2)$$

Hence the difference in available energy loss between an ordinary distillation column and a continuous heat integrated column is given by

$$\Delta E - \Delta E' = \left(1 - \frac{T_0}{T_H}\right)(Q_R - Q_R') - \left(1 - \frac{T_0}{T_c}\right)(Q_c - Q_c') - W_c$$

$$- T_0 \int_0^{Q_T}\left(\frac{1}{T_s} - \frac{1}{T_R}\right)dQ \quad (3)$$

Simplifying the result by assuming $Q_R \simeq Q_c = Q$:

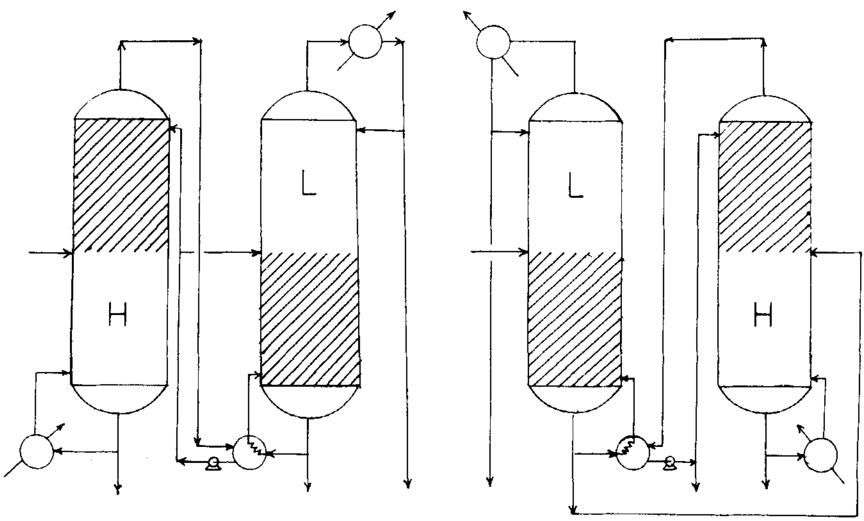

FIG. 2a. Application of the concentric column for two multicolumn system configurations.

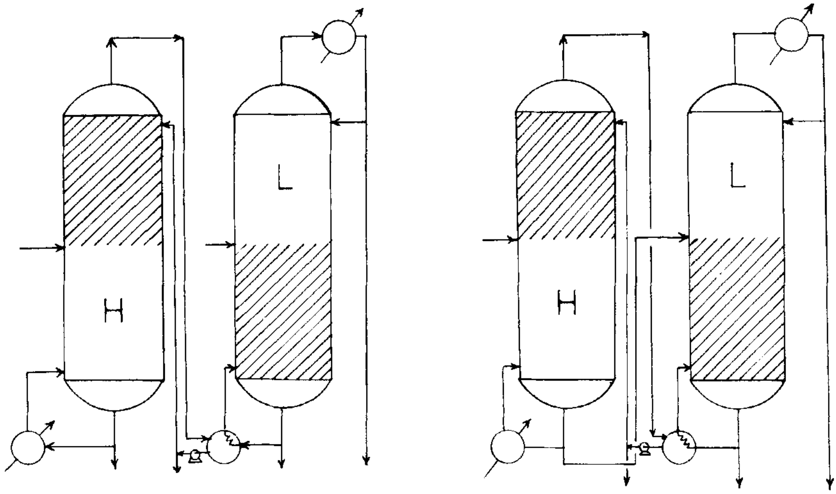

FIG. 2b. Application of the concentric column for two multicolumn system configurations.

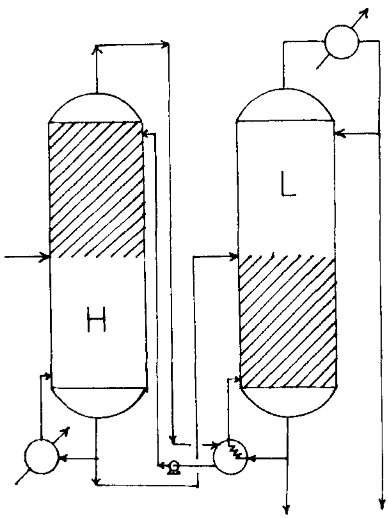

FIG. 2c. Application of the concentric column for a multicolumn system configuration.

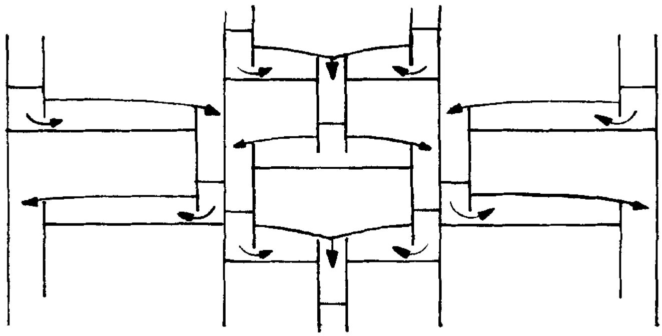

FIG. 3. Schematic of several possible designs for a heat integrated tray in a concentric column.

$$Q'_R = Q'_c = Q',\ T_s = T_H,\ T_R = T_c$$

Then

$$\Delta E - \Delta E' = T_0\left[\frac{T_H - T_c}{T_c T_H}\right][Q - Q' + Q_T] - W_c \qquad (4)$$

It will be shown later that $Q > Q'$, hence $(\Delta E - \Delta E') > 0$, which shows that the energy loss in a concentric column is less than in a conventional column. This result is consistent with the fact that a reversible column with minimum energy loss consists of an infinite number of condensers in the rectifying section and an infinite number of reboilers in the stripping section. The concentric column is simply a more practical though less efficient implementation of a reversible column.

MODEL DEVELOPMENT

From a degree of freedom analysis of the concentric column, the following design parameters are specified: stage pressures, feed conditions (component molar flow rates, temperature, and pressure), distillate product condition (component molar flow rates, temperature, and pressure), total number of stages, feed location, overall heat transfer coefficient for heat integrated stages, and external reflux ratio.

The *m*aterial flow rates, *e*quilibrium, *s*um of compositions, and *e*nthapy (*H*) (MESH) equations for each stage are summarized in Table 2. An

TABLE 2
Material, Equilibrium, and Energy Balance Equations for a Heat Integrated Tray in the Concentric Column

Material conservation:

$$L_{j-1}x_{j-1} - [V_j + W_j]y_j - [L_j + U_j]x_j + V_{j+1}y_{j+1} = -F_j z_j$$

Equilibrium equations:

$$y_j = K_j x_j \quad \text{or} \quad V_j y_j = K_j V_j x_j$$

$$\sum y_i = 1.0$$

$$\sum x_j = 1.0$$

Enthalpy equations:

$$L_{j-1}h_{j-1} - [V_j + W_j]H_j - [L_j + U_j]h_j + V_{j+1}H_{j+1} - Q_j = -F_j HF_j$$

$$Q_j = UA(T_R - T_S)$$

additional equation describing heat transfer between the heat integrated sections are also incorporated in the MESH equations.

MODEL CALCULATION PROCEDURE

The model equations are solved using successive approximations of the MESH equations for all stages. The procedure used is as follows:

1. Estimate temperatures, compositions, and internal flow rates for all stages with no heat transfer between the heat integrated stages
2. Estimate the heat transfer using the overall heat transfer coefficient and adiabatic tray temperatures
3. Recompute the temperatures, compositions, and internal flow rates with the heat transfer computed in Step 2
4. Converge on tray temperatures and heat transfer between the sections

UNIQUAC equations were used to compute vapor–liquid equilibrium.

The MESH equations for the adiabatic column in Step 1 were solved using a modified Boston and Sullivan algorithm (*26*).

RESULTS AND DISCUSSION

The main parameters distinguishing the concentric column from an ordinary adiabatic column are the overall heat transfer coefficient (*U*) and the heat transfer area (*A*) between the heat integrated stages.

The effect of *UA* on minimum reflux ratio, condenser and reboiler duties, and compression work was investigated. The system studied was ethylene–ethane to permit comparison with previous studies on the same system.

Figures 4 and 5 show the effects of interstage heat transfer applied to two pressure columns. Adiabatic operation (no heat transfer into or out of the column except at the reboiler and condenser) is represented along the $UA = 0$ ordinate. The minimum reflux ratio is achieved when the number of stages is infinite. When the reflux ratio approaches the minimum value, there is a dramatic increase in the number of stages. Adiabatic operation ($UA = 0$) to achieve the specified product compositions is not

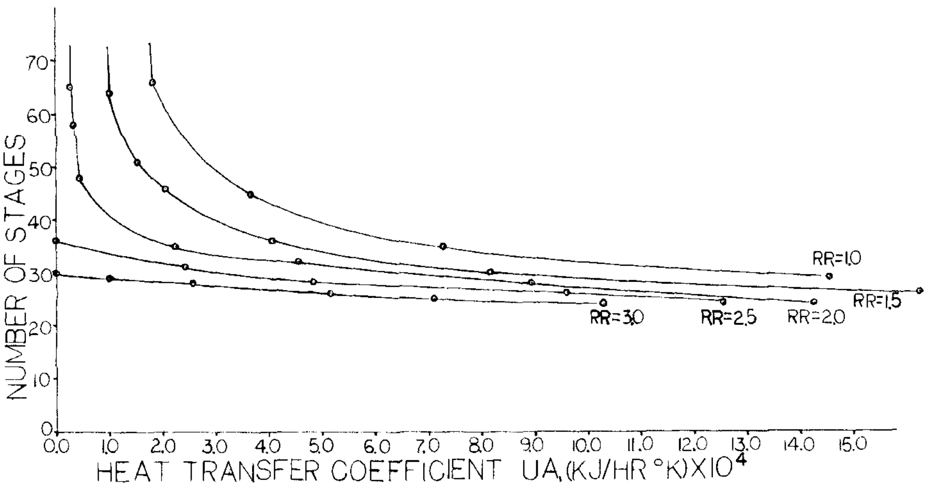

FIG. 4. Number of stages vs interstage heat transfer coefficient area at changing reflux ratio (RR). Ethylene–ethane, 0.5 mol fraction feed. Distillate purity ⩾ 0.995 ethylene. Bottoms purity ⩾ 0.995 ethane. Feed flow rate basis, 1000 kg · mol/h. $P_{\text{rectifying}} = 4.47$ bar. $P_{\text{stripping}} = 1.52$ bar.

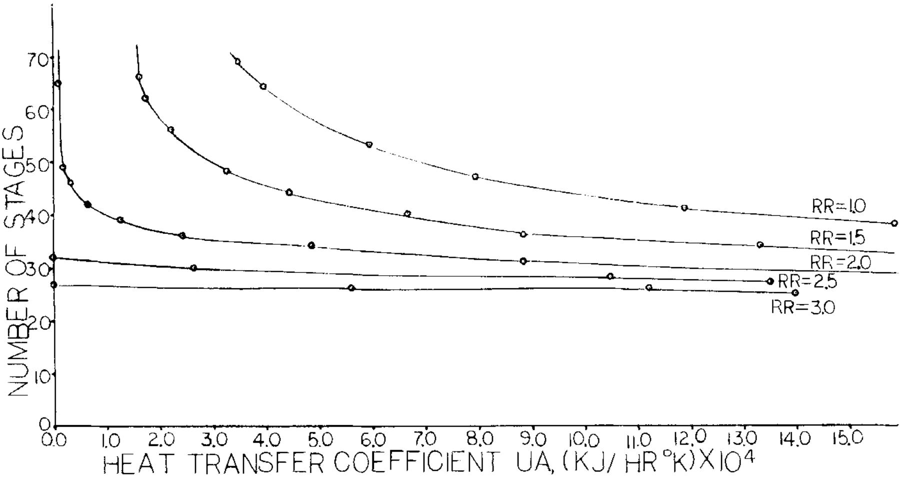

FIG. 5. Number of stages vs interstage heat transfer coefficient area at changing reflux ratio (RR). Conditions as in Fig. 4 except that $P_{rectifying}$ = 3.03 bar.

possible below a reflux ratio of 2.0. However, for a continuous heat integrated column with interstage heat transfer (*UA* = 0), it is possible to get the desired product compositions at a reflux ratio of less than 2.0.

Figure 4 is for a pressure ratio of 2.94. Figure 5 is for a pressure ratio of 1.99, with a stripping section pressure of 1.52 bars.

In Fig. 6 the minimum reflux ratio is plotted versus the product of the interstage heat transfer coefficient and the interstage heat transfer area (*UA*). The minimum reflux ratio decreases significantly as the term *UA* increases. Theoretically, at a large value of UA the minimum reflux ratio will become zero; however, in this example, since all the stages were not heat integrated due to differing number of trays in the rectifying and stripping sections, the minimum reflux ratio will eventually level off with increasing *UA*.

A continuous heat integrated column can be operated with or without vapor recompression. Vapor recompression significantly lowers the net steam consumption and investment cost for the heat exchangers. Hence, in a continuous heat integrated column with vapor recompression, there are two separate compressors: One compressor called the stripping rectifying compressor (SRC) maintains the rectifying section at a pressure higher than stripping and the other compressor is for vapor recompression (VRC).

In Fig. 7 the compressor work for the two compressors is plotted versus

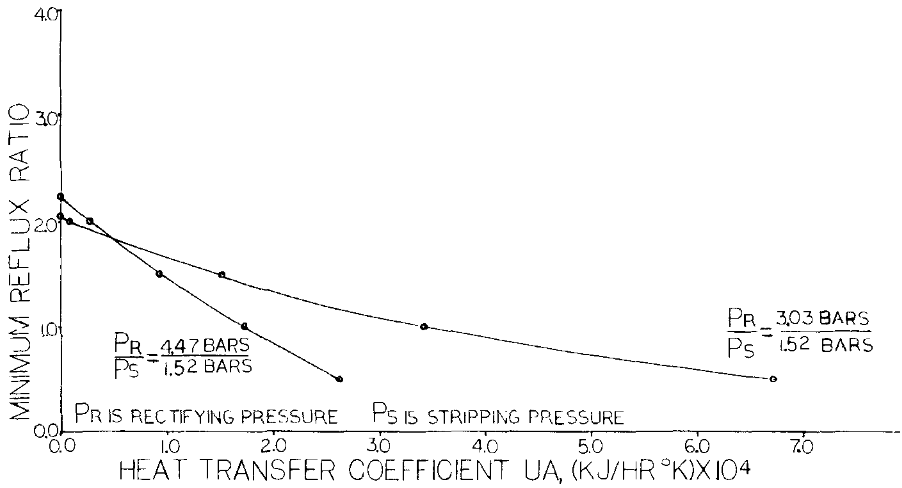

FIG. 6. Minimum reflux ratio versus interstage heat transfer coefficient area at different operating pressures. Conditions as in Figs. 4 and 5, and number of stages ⩾ 70.

the reflux ratio for a specified value of UA, feed flow rate, composition, and product compositions. Lower reflux rates require less work into the system to maintain necessary internal flow rates.

The effect of *UA* on the stripping-rectifying compressor work and the vapor recompression work is shown in Fig. 8. As is evident, with increasing heat transfer between the stages, the stripping-rectifying compressor work increases due to higher flow rates. The vapor recompression work remains almost constant with increasing *UA*.

In Fig. 9 seven case studies are compared for utility requirements. The seven cases are described in Table 3 and consist of adiabatic one-pressure column, adiabatic two-pressure column, and concentric column, with and without vapor recompression. Power consumption by compressors assumes a shaft work efficiency of 80%. Temperature drops at the condenser and reboiler were set at 20 K. Conventional column pressure was set at 4.47 bars. Two pressure columns had rectifying pressures of 4.47 bars and stripping pressures of 1.52 bars. For the adiabatic column the reflux ratio was set at 1.2 times the minimum reflux.

Vapor recompression significantly reduces net energy consumption for adiabatic columns. Present industry practices incorporate vapor recompression in ethylene–ethane separation. With interstage heat transfer, steam requirements for vapor recompression can be reduced by 21%.

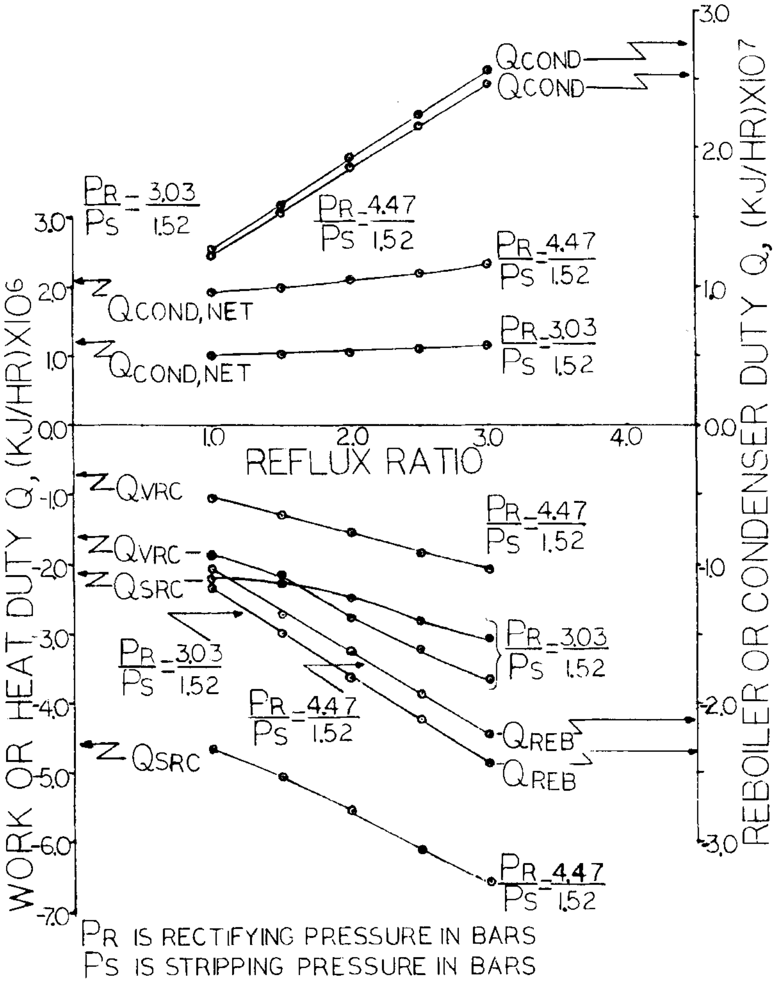

FIG. 7. Heat or work duties for compressors, condensers, and reboilers vs reflux ratio with changing operating pressures. Conditions as in Fig. 4 and $U' = 20{,}441.6$ kJ/h · m^2 · °K.

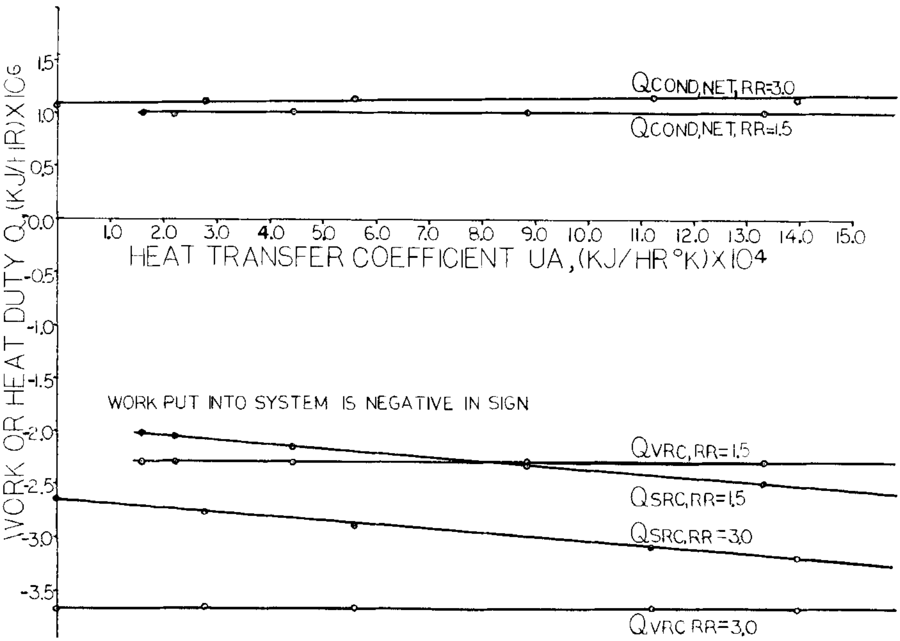

FIG. 8. Net condenser duty, $Q_{COND,NET}$, stripping to rectifying compressor work, Q_{SRC}, and vapor recompression work, Q_{VRC}, vs interstage head transfer coefficient area at changing reflux ratio (RR). Conditions as in Fig. 5.

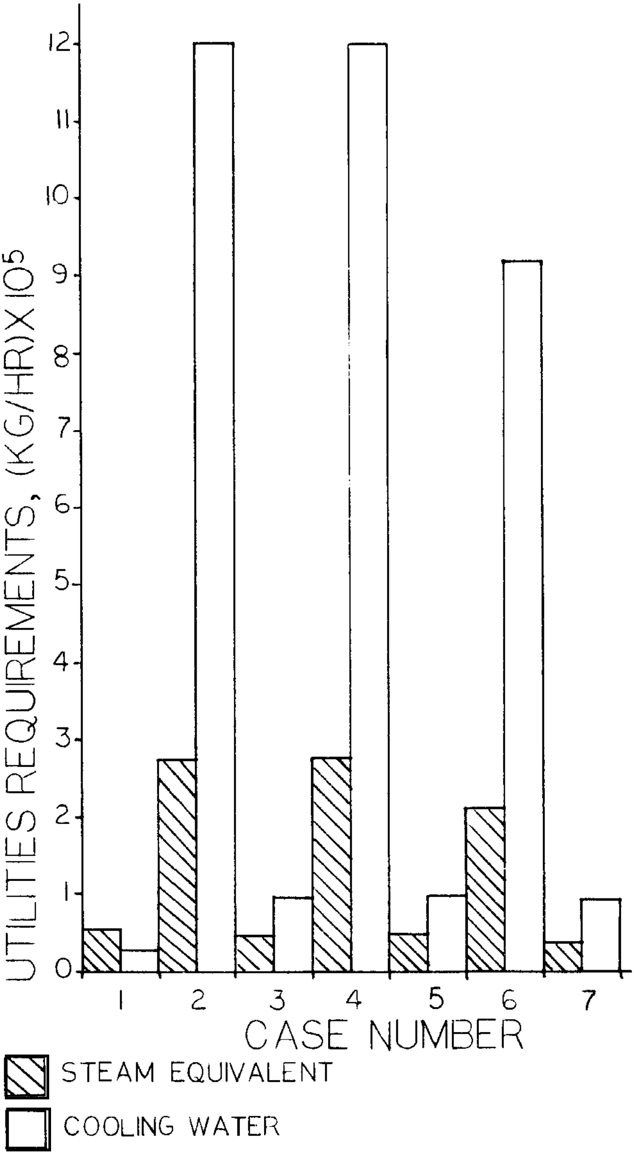

FIG. 9. A comparison of utility requirements for seven case studies.

TABLE 3
Comparison Case Studies of Adiabatic Two-Pressure Column Operation with Concentric Column Operation[a]

Case[b]	Reflux ratio	Q_R, (kJ/h) $\times 10^7$	Q_C, (kJ/h) $\times 10^7$	Q_{SRC}, (kJ/h) $\times 10^6$	Q_{VRC}, (kJ/h) $\times 10^6$	Steam equivalent, (kJ/h) $\times 10^5$	Cooling water, (kJ/h) $\times 10^5$
1	2.67	−2.225	2.264	0.000	−1.529	0.5066	0.2075
2	2.67	−2.087	2.264	−3.889	0.000	2.735	12.04
3	2.67	−2.087	2.264	−3.889	−1.921	0.4374	0.9416
4	2.67	−2.077	2.264	−4.480	0.000	2.763	12.04
5	2.67	−2.077	2.264	−4.480	−1.921	0.4773	0.9948
6	1.80	−1.554	1.727	−3.736	0.000	2.109	9.187
7	1.80	−1.554	1.727	−3.736	−1.464	0.3999	0.9203

1 Adiabatic one-pressure column with vapor recompression
2 Adiabatic two-pressure column without vapor recompression
3 Adiabatic two-pressure column with vapor recompression
4 Concentric column without vapor recompression
5 Concentric column with vapor recompression
6 Concentric column without vapor recompression
7 Concentric column with vapor recompression

[a]Note that the minimum reflux for adiabatic column operation is 2.225 while the minimum reflux of the concentric column operation is 0.92. The concentric column operation reflux was selected with a comparable number of stages with the adiabatic two-pressure column at a reflux ratio of 1.2 times the minimum adiabatic reflux ratio.

[b]The one pressure adiabatic column is operated at 1.2 times the minimum adiabatic reflux and at 4.47 bars pressure. For Cases 2 to 5 the columns are operated at 1.2 times the minimum adiabatic reflux, 4.47 bars rectifying pressure, and 1.52 bars stripping pressure. Case 7 operates at 2.0 times the minimum reflux for interstage operation of $U = 4088.32$ kJ/(h · m^2 · °K) with 4.47 bars rectifying pressure and 1.52 bars stripping pressure. The reflux ratio selected for Case 7 was chosen in order to give a comparable number of stages.

SYMBOLS

A	area of heat transfer between the rectifying and stripping sections
c	number of components in the feed
C_D, C_F, C_W	specific heat for distillate, feed, and bottoms, respectively
D	distillate rate
F	feed rate
F_j	feed rate to the jth tray
h_j, H_j	enthalpy of stream leaving tray j for liquid and vapor phase, respectively
HF_j	enthalpy of F_j
K_j	equilibrium constant
L_j	liquid rate leaving tray j
Q_j	heat removed from tray j
Q_t	total heat transferred between the rectifying and stripping sections
Q_c, Q_R	condenser and reboiler duties, respectively, for an ordinary column
Q'_c, Q'_R	condenser and reboiler duties, respectively, for a concentric column
R	gas constant
T_0	reference temperature
T_c	condenser temperature
T_H	reboiler temperature
T_F, T_D, T_W	temperature of feed, distillate, and bottom product, respectively
T_S, T_R	temperature at a given height in the stripping and rectifying sections, respectively
U	overall heat transfer coefficient between the rectifying and stripping sections
U_j	liquid side stream flow rate from stage j
V_j	vapor flow rate leaving stage j
W_j	vapor sidestream flow rate from stage j
W_c	compressor work in a concentric column
x_j	mole fraction composition of L_j leaving stage j
X_{Fi}	mole fraction of component i in the feed
Y_j	mole fraction composition of V_j leaving stage j
z_j	feed mole fraction composition for stage j

Greek

ΔE	available energy loss for an ordinary distillation column
$\Delta E'$	available energy loss for a concentric distillation column

REFERENCES

1. M. J. Andrecovich and A. W. Westerberg, *AIChE J., 31,* 363 (1985).
2. M. A. Menzies and A. I. Johnson, *Can. J. Chem. Eng., 50,* 290 (1972).
3. M. Morari and D. C. Faith, *AIChE J., 26,* 916 (1980).
4. Y. Naka, M. Terashita, and T. Takamatsu, *Ibid., 28,* 812 (1982).
5. R. N. S. Rathore, K. A. V. Wormer, and G. J. Powers, *Ibid., 20,* 940 (1974).
6. R. N. S. Rathore, *Chem. Eng., 89,* 155 (1982).
7. L. Schluter and R. Schmidt, *Int. Chem. Eng., 23,* 427 (1983).
8. W. D. Tedder and D. F. Rudd, *AIChE J., 24,* 334 (1978).
9. T. P. Chiang and W. L. Luyben, *Ind. Eng. Chem., Process Des. Dev., 22,* 175 (1983).
10. N. G. O'Brian, *Chem. Eng. Prog., 72,* 65 (1976).
11. W. C. Patterson and T. A. Wells, *Chem. Eng., 84,* 79 (1977).
12. B. K. Tyrens and W. L. Luyben, *Hydrocarbon Process., 54,* 93 (1975).
13. T. Umeda, N. Kazuo, and S. Katsuo, *AIChE J., 25,* 423 (1979).
14. F. B. Petlyuk, V. M. Platonov, and D. M. Slavinski, *Int. Chem. Eng., 5,* 555 (1965).
15. W. J. Stupin and F. J. Lockhart, *Chem. Eng. Prog., 68,* 71 (1972).
16. R. Danziger, *Ibid., 75,* 58 (1979).
17. S. Finelt, *Hydrocarbon Process., 58,* 95 (1979).
18. J. Flores, F. Castells, and J. A. Ferre, *Ibid., 63,* 59 (1975).
19. Y. Naka, M. Terashita, S. Hayashiguchi, and T. Takmatsu, *Kagaku Kogaku, 13,* 123 (1980).
20. H. R. Null, *Chem. Eng. Prog., 72,* 58 (1976).
21. G. P. Quadri, *Hydrocarbon Process., 60,* 119 (1981).
22. F. Kayihan, Paper Presented at the 70th Annual AIChE Meeting, New York, 1977.
23. R. E. Fitzmorris and R. S. H. Mah, *AIChE J., 26,* 265 (1980).
24. R. S. H. Mah, J. J. Nicholas, and R. B. Wodnik, *Ibid., 23,* 651 (1977).
25. K. Shimizu and R. S. H. Mah, *Comput. Chem. Eng., 7,* 105 (1983).
26. J. F. Boston and S. L. Sullivan, *Can. J. Chem. Eng., 50,* 663 (1972).

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