Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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Ho-Ming Yeh[a]; Shau-Wei Tsai[a]
[a] CHEMICAL ENGINEERING DEPARTMENT, NATIONAL CHENG KUNG UNIVERSITY TAINAN, TAIWAN, REPUBLIC OF CHINA

To cite this Article Yeh, Ho-Ming and Tsai, Shau-Wei(1982) 'Separation Efficiency of Rotary Thermal Diffusion Columns with the Inner Tube Cooled and the Outer Tube Heated', Separation Science and Technology, 17: 8, 1075 — 1083
To link to this Article: DOI: 10.1080/01496398208060271
URL: http://dx.doi.org/10.1080/01496398208060271

SEPARATION SCIENCE AND TECHNOLOGY, 17(8), pp. 1075–1083, 1982

Separation Efficiency of Rotary Thermal Diffusion Columns with the Inner Tube Cooled and the Outer Tube Heated

HO-MING YEH and SHAU-WEI TSAI

CHEMICAL ENGINEERING DEPARTMENT
NATIONAL CHENG KUNG UNIVERSITY
TAINAN, TAIWAN, REPUBLIC OF CHINA

Abstract

Adjusting the temperature gradient to the opposite direction in rotary thermal diffusion columns results in improving the separation efficiency. In the case of small σ', even this modified rotary column gives better separation than the original rotary one developed in previous work.

INTRODUCTION

Sullivan, Ruppel, and Willingham (*2*) found from their experimental work that the rotary thermal diffusion column gave better separation than the stationary one, especially for highly viscous fluids. However, the motion in the rotary columns, as used by Sullivan et al., in which the inner tube rotates and the outer one is at rest, may become unstable with respect to three-dimensional disturbances in analogy with the boundary layer on a concave wall. Schultz-Grunow (*1*) has shown from experimental results that the flow between two concentric tubes of which the outer rotates and the inner is at rest is completely stable. Therefore, the type of column tested by Schultz-Grunow has been recommended for use as a rotary thermal diffusion column (*3*).

The separation theory of rotary thermal diffusion column was presented by Yeh and Cheng (*3*). In their theoretical work the effect of curvature on the transport coefficient of thermal diffusion was neglected. Later, the separation theory was improved by Yeh and Tsai under consideration of the curvature effect (*4*). In our previous work a concentric-tube thermal diffusion column with the inner tube heated and the outer tube cooled was considered.

However, due to the curvature effect, the transport phenomena of thermal diffusion will be quite different if the temperature gradient in the column is adjusted to the opposite direction.

It is the purpose of this work to develop the separation theory of this modified column and to compare the separation efficiencies obtained in the original and modified rotary columns.

COLUMN THEORY

The separation equation for thermal diffusion in a rotary concentric-tube column with the inner tube heated and the outer tube cooled was given by Yeh and Tsai (*4*):

$$\Delta' = \frac{F(k,\ \mathrm{Br})}{2}\left[1 - \exp\left(\frac{-\sigma'}{2G(k,\ \mathrm{Br})}\right)\right] \tag{1}$$

where

$$\Delta' = \Delta\sigma/H_0 \tag{2}$$

$$\sigma' = \sigma L/K_0 \tag{3}$$

$$H_0 = \frac{2\pi R\alpha\rho\beta_{\bar{T}}g(\Delta T)^2[R(k-1)]^3}{6!\mu\bar{T}} \tag{4}$$

$$K_0 = \frac{2\pi R\rho\beta_{\bar{T}}^2 g^2(\Delta T)^2[R(k-1)]^7}{9!D\mu^2} \tag{5}$$

and the modifying factors, $F(k,\ \mathrm{Br})$ and $G(k,\ \mathrm{Br})$ were presented graphically. Under the same assumptions, the equation of separation for the column with the inner tube cooled and the outer tube heated may now be obtained by following the same derivation performed in obtaining the original rotary column:

$$\Delta_1' = \frac{F_1(k,\ \mathrm{Br})}{2}\left[1 - \exp\left(\frac{-\sigma'}{2G_1(k,\ \mathrm{Br})}\right)\right] \tag{6}$$

where $F_1(k,\ \mathrm{Br})$ and $G_1(k,\ \mathrm{Br})$ are given in Figs. 1 and 2, respectively.

For a nearly flat-plate column, $k \to 1$, the solution was obtained by Yeh, Cheng, and Tsai (*3, 4*) as

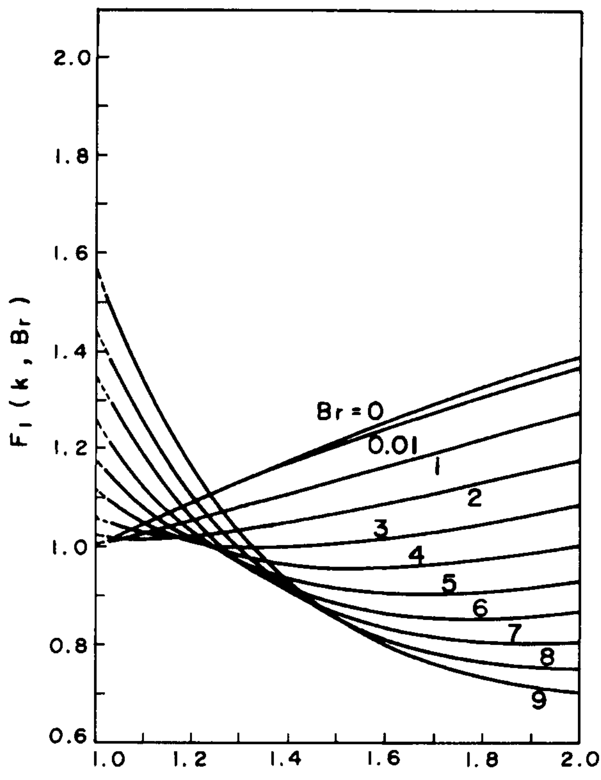

FIG. 1. Graphical representation of modifying factor.

$$\Delta_2' = \frac{F_2(\mathrm{Br})}{2}\left[1 - \exp\left(\frac{-\sigma'}{2G_2(\mathrm{Br})}\right)\right] \tag{7}$$

where

$$F_2(\mathrm{Br}) = 1 + \frac{\mathrm{Br}^2}{140} \tag{8}$$

$$G_2(\mathrm{Br}) = 1 + \frac{\mathrm{Br}^2}{1100} \tag{9}$$

It is noted that $F \approx F_1 \approx F_2$ and $G \approx G_1 \approx G_2$ as $k \rightarrow 1$ and both Eqs. (1) and (6) reduce to Eq. (7). Moreover, Eqs. (1), (6), and (7) reduce to Eq. (10) as $k \rightarrow 1$ and Br = 0.

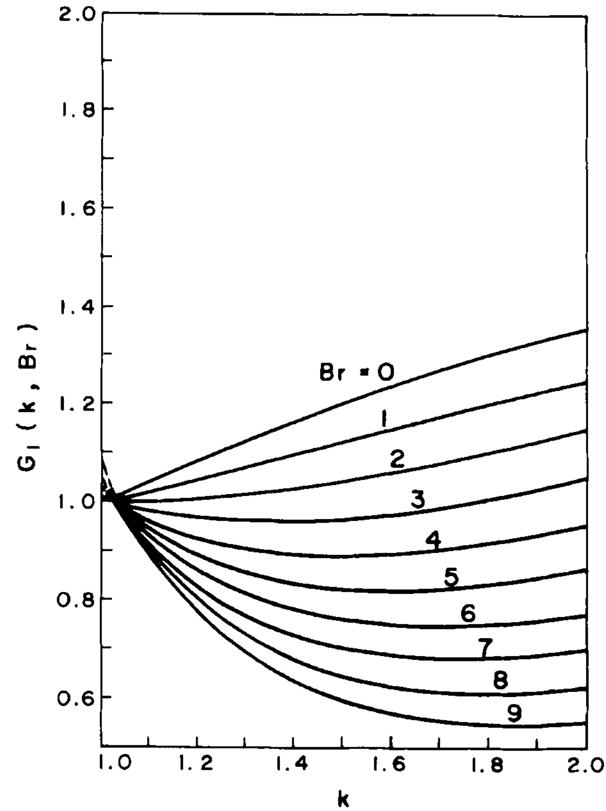

FIG. 2. Graphical representation of modifying factor.

$$\Delta_0' = \frac{1}{2}[1 - e^{-\sigma'/2}] \qquad (10)$$

Equation (10) is the separation equation for a Clusius-Dickel column of flat-plate type.

COMPARISON OF SEPARATION

Generally, the comparison of Δ and Δ_1 may be made from Eqs. (1) and (6) and the results depend on the parameters k, Br, and σ'. The values of k are usually close to unity for the practical design of concentric-tube thermal diffusion columns, therefore, G, and G_1 are also not far from unity. Consequently, as σ' is bigger than 10, Eqs. (1) and (6) reduce to

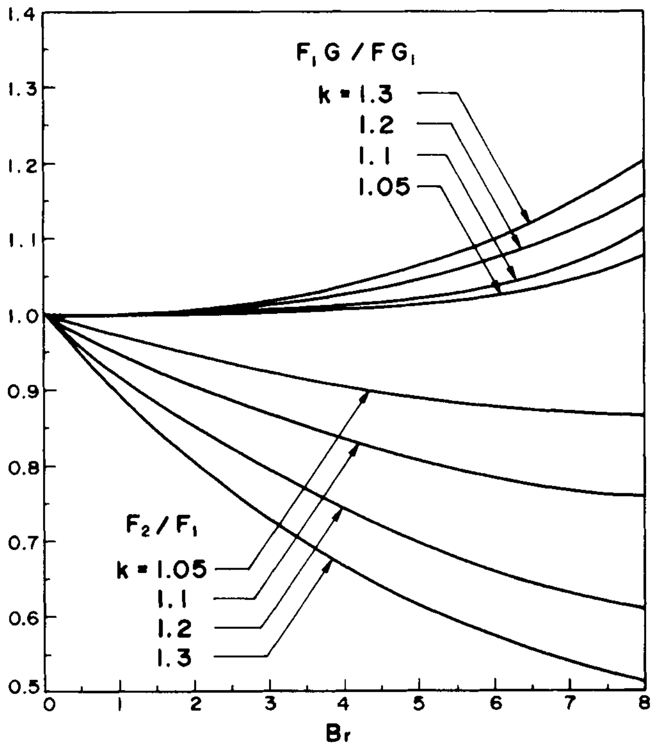

FIG. 3. Some combinations of modifying factors.

$$\Delta' = \frac{F(k,\ \mathrm{Br})}{2}$$

$$\Delta_1' = \frac{F_1(k,\ \mathrm{Br})}{2}$$

Thus

$$\Delta_1/\Delta = \Delta_1'/\Delta' = F_1/F$$

Since F_1/F is smaller than unity as shown in Fig. 3, we conclude that the original rotary column is recommended for use as σ' is larger than 10, especially for higher values of k and Br.

For small σ', say $\sigma' < 0.1$, Eqs. (1) and (6) reduce to the following by expanding the exponential terms in the Maclaurin series

$$\Delta' = F\sigma'/4G$$

$$\Delta_1' = F_1\sigma'/4G_1$$

Thus

$$\Delta_1/\Delta = \Delta_1'/\Delta' = F_1G/FG_1$$

Since the values of F_1G/FG_1 are higher than unity as shown in Fig. 3, we conclude that the modified rotary column is recommended for use because σ' is smaller than 0.1, especially for higher values of k and Br.

For the values of σ' between 0.1 and 10, comparison of Δ with Δ' can be obtained from Eqs. (1) and (6). The improvement of separation of concentric-tube columns with their outer tube rotated is best illustrated by calculating the percentage increase in separation based on the stationary column with the inner tube heated and the outer tube cooled:

$$I = \frac{\Delta' - (\Delta')_{BR=0}}{(\Delta')_{Br=0}} = \frac{\Delta - (\Delta)_{Br=0}}{(\Delta)_{Br=0}} \tag{11}$$

$$I_1 = \frac{\Delta_1' - (\Delta')_{Br=0}}{(\Delta')_{Br=0}} = \frac{\Delta_1 - (\Delta)_{Br=0}}{(\Delta)_{Br=0}} \tag{12}$$

Some values of I were calculated and are listed in Tables 1 and 2.

DISCUSSION AND CONCLUSION

The equation of separation for a rotary concentric-tube thermal diffusion column with the inner tube cooled and the outer tube heated has been derived. The most important assumptions in obtaining this modified column are that the concentration in the column is anywhere between 0.3 and 0.7 weight fraction and that only moderate flow rates are considered.

It was pointed out in our previous work that considerable improvement in separation was obtained by employing an original rotary column of which the inner tube was heated and the outer tube was cooled. This study shows that the degree of separation is also improved by adjusting the temperature gradient to the direction opposite of the original rotary column. However, in the case of large σ' and small Br, even the modified rotary column is worse than the stationary column as showed in Tables 1 and 2.

Furthermore, the modified rotary column is better than the original one when σ' is small, while the original column is better than the modified one

TABLE 1

The Improvement of Separation ($k = 1.1$)

	$\sigma' = 0.1$		$\sigma' = 1.0$		$\sigma' = 10$	
Br	I (%)	I_1 (%)	I (%)	I_1 (%)	I (%)	I_1 (%)
0	0.00	0.00	0.00	−0.10	0.00	−0.46
1	0.00	0.00	0.60	−0.50	2.73	−2.29
3	4.01	4.49	5.76	3.11	12.43	−1.67
5	11.02	13.06	13.93	10.72	25.80	3.44
7	20.41	28.57	24.75	24.95	44.51	13.33
8	25.31	37.96	30.36	33.47	54.46	19.60

TABLE 2

The Improvement of Separation ($k = 1.2$)

	$\sigma' = 0.1$		$\sigma' = 1.0$		$\sigma' = 10$	
Br	I (%)	I_1 (%)	I (%)	I_1 (%)	I (%)	I_1 (%)
0	0.00	0.82	0.00	0.75	0.00	0.04
1	0.41	1.23	1.05	−0.25	4.76	−3.32
3	4.51	5.74	6.68	3.24	17.02	−5.28
5	8.61	13.11	12.67	8.28	31.57	−6.73
7	15.57	26.23	21.15	19.05	50.57	−2.47
8	18.85	35.66	25.49	26.93	61.67	1.74

when σ' is large. This conclusion will be more evident if both k and Br increase.

SYMBOLS

Br	Brinkman number, defined by $\mu V^2/\lambda(\Delta T)$
D	ordinary diffusion coefficient
$F(k, \mathrm{Br})$	modifying factor, evaluated by Eq. (13) of Ref. *4*
$F_1(k, \mathrm{Br})$	modifying factor, presented in Fig. 1
$F_2(\mathrm{Br})$	modifying factor, evaluated by Eq. (8)
$G(k, \mathrm{Br})$	modifying factor, evaluated by Eq. (14) of Ref. *4*
$G_1(k, \mathrm{Br})$	modifying factor, presented in Fig. 2

$G_2(\mathrm{Br})$	modifying factor, evaluated by Eq. (9)
g	gravitational acceleration
H_0	system constant, evaluated by Eq. (4)
I, I_1	improvement of separation defined by Eqs. (11) and (12)
K_0	system constant, evaluated by Eq. (5)
L	column length
R	outside radius of inner tube
kR	inside radius of outer tube
T	absolute temperature
T_1, T_2	temperature of hot, cold wall
ΔT	$T_1 - T_2$
$\bar{T}$	reference temperature
V	tangential velocity of outer tube rotated

Greek Letters

α	thermal diffusion constant
$\beta_{\bar{T}}$	$-(\partial\rho/\partial T)_{\bar{T}}$
Δ, Δ_1	Difference of mass fraction of Component 1 between top and bottom products in the original rotary column and in the modified rotary column
Δ_2	Δ or Δ_1 obtained as $k \to 1$
Δ'	$\Delta\sigma/H$
λ	thermal conductivity of fliud
μ	viscosity of fluid
ρ	mass density
σ	mass flow rate
σ'	$\sigma L/K_0$

Acknowledgment

The authors wish to express their thanks to The Chinese National Science council for financial aid.

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Received by editor August 28, 1981