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A Study on the Separation Efficiencies of Rotating-Tube Wired Thermal-Diffusion Columns under Higher Flow-Rate Operations

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Abstract

Even under higher flow-rate operations, $\sigma' > 0.42A^2$, rotating the tubes oppositely in a wired concentric-tube thermal diffusion column still substantially increases the separation efficiency by improving the cascading effect. The equations for estimating the best tube speed of rotation and maximum separation, with the inclination of the wire angles as parameters, have been derived. The maximum separation increases as the inclination of the wire angle decreases; however, this also leads to increasing the best tube speed of rotation and thereby raising the operating cost.

INTRODUCTION

A number of improved thermal diffusion columns have been developed in which the desirable cascading effect is increased and/or the undesirable remixing effect is reduced, and thereby lead to improved separation (*5–12, 14, 18–22*). The application of linear fluid shear in thermal diffusion columns was first investigated by Ramser (*7*). He demonstrated that the separation efficiency of a batch-type flat-plate thermal diffusion column placed in a horizontal position could be improved with walls set in parallel opposite motion. In 1972, Yeh and Tsai pointed out that the optimal angle of inclination also exists in such moving-wall columns (*10*). Later, Yeh and Ho reported that the phenomena of thermal diffusion in a wired concentric-tube column with tubes rotated in opposite directions is equivalent to that in an inclined flat-plate column with walls set in opposite motion (*14*). It has been

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also found that the maximum separation obtainable in a rotating-tube wired column is exactly the same as that in a moving-wall inclined column. Since the construction and operation of a rotating-wall inclined column is much easier than those of a moving-wall inclined one, the former is recommended for use.

The optimal wire angle of inclination in rotating-tube wired columns exists only for lower flow-rate operations, i.e., $\sigma' A^{-2} < 0.42$. However, the installation of spiral wires in concentric-tube thermal diffusion columns is still required for conducting the fluid shear to produce the cascading effect in the transport direction, even when $\sigma'/A^2 > 0.42$. The principal purpose of this work is to investigate the effect of fluid shear on the separation efficiencies of rotating-tube wired thermal diffusion columns under higher flow-rate operations.

WIRED COLUMN WITH TUBES ROTATED IN OPPOSITE DIRECTIONS UNDER LOWER FLOW-RATE OPERATIONS

The wired thermal diffusion column with tubes rotated in opposite directions was introduced by Yeh and Ho (*14*). They considered a concentric-tube thermal diffusion column with smaller annular spacing and a tight fitting wire spiral, having a diameter equal to annular spacing, wrapped on the entire inner tube as shown in Fig. 1. During operation, the outer tube is heated while the inner tube is cooled, and both tubes are rotated in opposite directions. The equation of separation is

$$\Delta_1' = \frac{A\Phi - 5X(\Phi - \phi^2)^{1/2}}{4\sigma'} \times \left(1 - \exp\frac{-\sigma'}{A^2\Phi^2 + \Phi - 9AX(\Phi^3 - \Phi^4)^{1/2} + 21X^2(\Phi - \Phi^2)}\right) \quad (1)$$

$$H_0 = \frac{2\pi R_1 \alpha \bar{\beta}_T \bar{\rho} g (R_2 - R_1)^3 (\Delta T)^2}{6!\mu \bar{T}} \quad (2)$$

$$K_0 = \frac{2\pi R_1 \bar{\beta}_T^2 \bar{\rho} g^2 (\Delta T)^2 (R_2 - R_1)^7}{9!\mu^2 D} \quad (3)$$

$$K_d = 2\pi R_1 D\bar{\rho}(R_2 - R_1) \quad (4)$$

$$X = \left(\frac{2\omega}{\sqrt{630D}}\right) V \quad (5)$$

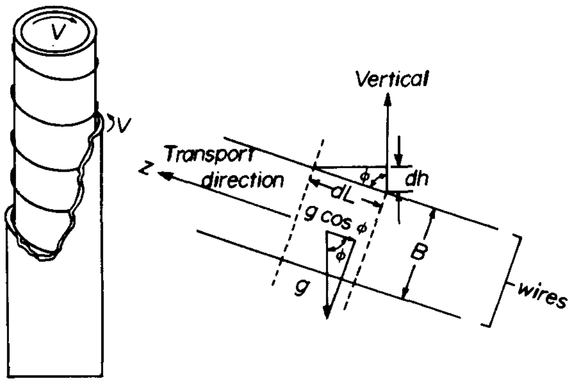

FIG. 1. Spiral wire inserted as a spacer in the annulus of a concentric-tube thermal diffusion column with tubes rotated oppositely.

$$\Phi = \cos^2 \phi \tag{6}$$

$$\sigma' = \sigma h / 2K_d \tag{7}$$

$$\Delta_I' = \frac{\sqrt{K_0 K_d}}{H_0 h} \Delta_I \tag{8}$$

$$A = \sqrt{K_0 / K_d} \tag{9}$$

In the derivation of Eq. (1), the effect of tube curvature was neglected because of the diminutive size of the annular spacing. It was also assumed that the concentration in the column is anywhere between 0.3 and 0.7 weight fraction. For the whole range of concentration, some suitable correction is necessary, as shown by Yeh et al. (*13, 15–17, 21*).

Equation (1) can be used to obtain the optimal conditions for maximum separation. Yeh and Ho obtained the best tube-speed of rotation and best wire-angle of inclination for maximum separation by partially differentiating Eq. (1) with respect to X and Φ, respectively, and setting $\partial \Delta_I'/\partial X = 0$ and $\partial \Delta_I'/\partial \Phi = 0$. The results are

$$\phi_{I,\text{best}} = \frac{-14 + \sqrt{21 + 3A^2\sigma'/y}}{A^2} \tag{10}$$

$$X_{1,\text{best}} = \frac{A^2\Phi_{1,\text{best}} + 5}{3A\sqrt{\Phi_{1,\text{best}} - \Phi^2_{1,\text{best}}}} \tag{11}$$

$$|\Delta'_1|_{\max} = \frac{-3 + 2\sqrt{21 + 3A^2\sigma'/y}}{12\sigma' A}(1 - e^{-y}) \tag{12}$$

provided that

$$e^y = 1 + 2y + \frac{y^2(14 - \sqrt{21 + 3A^2\sigma'/y})}{\sigma' A^2} \tag{13}$$

Unlike the flows of fluxes in a stationary column, Component 1, which accumulates near the hot wall, will be transferred downward by the linear fluid shear which plays the role of increasing the cascading effect, while the natural convective flow plays the role of reducing the remixing effect. Therefore, separation obtained under optimal conditions is always negative. Since A and σ' are generally greater than 100 and 1000, respectively, and $y \approx 1.26$, Eqs. (10), (11), and (12) reduce to

$$\Phi_{1,\text{best}} = 1.55\sigma'^{1/2}A^{-1} \tag{14}$$

$$X_{1,\text{best}} = 0.513A(1.55\sigma'^{-1/2}A - 2.38)^{-1/2} \tag{15}$$

$$|\Delta'_1|_{\max} = 0.184\sigma'^{-1/2} \tag{16}$$

They also pointed out that the existance of the best wire angle of inclination is restricted by the following range of flow rate, according to the fact that $\phi_{1,\text{best}} \leq 1$,

$$\sigma' \leq 0.42A^2 \tag{17}$$

WIRED COLUMN WITH TUBES ROTATED IN OPPOSITE DIRECTIONS UNDER HIGHER FLOW-RATE OPERATIONS

In fact, for flow rates exceeding this critical value, the inclination decreases the separation. Since the inclination of the wire spiral in a rotated column plays the important role of conducting the fluid shear for producing the cascading effect in the transport direction, separations obtainable in a wired column operating at the best tube speed of rotation might therefore be still better than those obtainable in the same column operating with stationary tubes, even when $\sigma' > 0.42A^2$. For this reason, the effect of the wire angle on the degree of separation in rotated wired thermal diffusion columns will be investigated further for σ' greater than $0.42A^2$. The best tube speed of rotation, with the inclination of wire angles as parameters, is obtained from Eq. (1) by setting $\partial\Delta_1'/\partial X = 0$. The results are

$$\dot{X}_{1,\text{best}} = \frac{9A\Phi + \sqrt{84\left(\frac{\sigma'}{y} - \Phi\right) - 3A^2\phi^2}}{42(\Phi - \Phi^2)^{1/2}} \tag{18}$$

$$|\dot{\Delta}_1'|_{\max} = \frac{3A\Phi + 5\sqrt{84\left(\frac{\sigma'}{y} - \Phi\right) - 3A^2\Phi^2}}{168\sigma'}(1 - e^{-y}) \tag{19}$$

provided that

$$e^y = 1 + 2y - \frac{2\Phi y^2}{\sigma'} - \frac{y^2A^2\Phi^2}{14\sigma'}\left(1 - \frac{0.2}{A\Phi}\sqrt{84\left(\frac{\sigma'}{y} - \Phi\right) - 3A^2\Phi^2}\right) \tag{20}$$

Furthermore, we may assume that when $\sigma'/y\Phi \gg 1$ and $\sigma'/y^2\Phi \gg 1$, Eqs. (18), (19), and (20) reduce to, after rearrangement,

$$\dot{X}_{1,\text{best}} = A\Phi\left[\frac{9 + \sqrt{\frac{84}{y\Phi^2}\left(\frac{\sigma'}{A^2}\right) - 3}}{42(\Phi - \Phi^2)^{1/2}}\right] \tag{21}$$

$$\sigma'^{-1/2}|\dot{\Delta}_1'|_{\max} = \frac{\Phi\left[3 + 5\sqrt{\frac{84}{y\Phi^2}\left(\frac{\sigma'}{A^2}\right) - 3}\right](1 - e^{-y})}{168\left(\frac{\sigma'}{A^2}\right)^{1/2}} \tag{22}$$

$$e^y = 1 + 2y - \frac{y^2\Phi^2}{14}\left(\frac{A^2}{\sigma'}\right)\left[1 - 0.2\sqrt{\frac{84}{y\Phi^2}\left(\frac{\sigma'}{A^2}\right) - 3}\right] \tag{23}$$

Some values of $X_{1,\text{best}}$ and $|\dot{\Delta}_1'|_{\max}$ are calculated and presented graphically in Figs. 2 and 3, respectively, for convenient use. It is easy to show that Eqs. (21), (22), and (23) have solutions only when, according to the restriction $(84/y\Phi)(\sigma'/A^2) - 3 \geq 0$,

$$\sigma' \geq \frac{y\Phi^2}{28} A^2 \tag{24}$$

WIRED COLUMN WITH ONE TUBE ROTATED

Fluid shear can also be created by rotating only one tube in the wired columns. The equation of separation in such columns is obtained by following the same derivation performed in Yeh and Ho's work (*14*). The solution is

$$\Delta_2' = \frac{A\Phi \pm 5X(\Phi - \Phi^2)^{1/2}}{4\sigma'} \times \left[1 - \exp \frac{-\sigma'}{A^2\Phi^2 + \Phi \pm 9AX(\Phi^3 - \Phi^4)^{1/2} + 24X^2(\Phi - \Phi^2)}\right] \tag{25}$$

in which the choice of plus or minus sign depends on either the cold tube or the hot tube being rotated. The best tube speed of rotation and the best wire angle of inclination for maximum separation in a wired column are obtained by partially differentiating Eq. (25) with respect to X and Φ, respectively, and setting $\partial\Delta_2'/\partial X = 0$ and $\partial\Delta_2'/\partial\Phi = 0$. After simplification, we have

$$\phi_{2,\text{best}} = \frac{-32 + \sqrt{24 + 15A^2\sigma'/y}}{10A^2} \tag{26}$$

$$X_{2,\text{best}} = \frac{\pm(A^2\Phi_{2,\text{best}} + 5)}{3A(\Phi_{2,\text{best}} - \Phi_{2,\text{best}}^2)^{1/2}} \tag{27}$$

$$|\Delta_2'|_{\max} = \frac{-3 + 4\sqrt{24 + 15A^2\sigma'/y}}{60\sigma'A}(1 - e^{-y}) \tag{28}$$

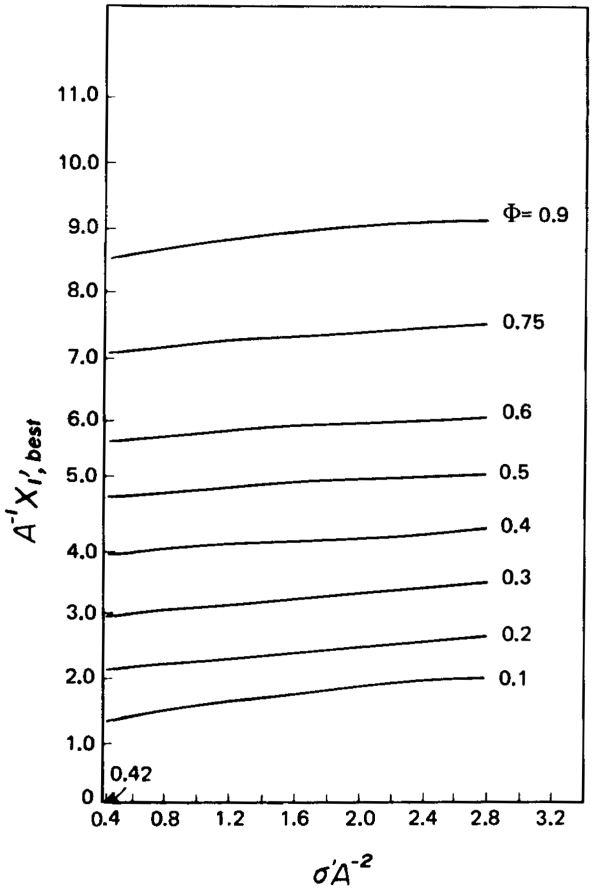

FIG. 2. The best tube-speed of rotation for maximum separation in a rotated wired thermal diffusion column.

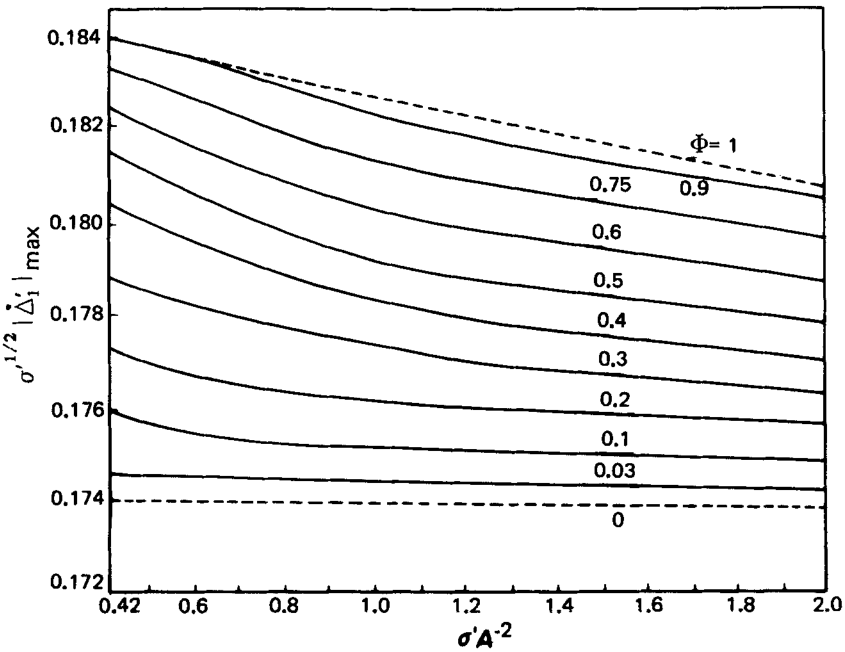

FIG. 3. The maximum separation obtainable in a rotated wired column under higher flow-rate operations.

provided that

$$e^y = 1 + 2y + \frac{y^2(32 - \sqrt{24 + 15A^2\sigma'/y})}{10\sigma' A^2} \tag{29}$$

The plus and minus signs in Eq. (27) also denote the cold tube rotated and the hot tube rotated, respectively. For $A > 100$, $\sigma' > 1000$, and $y \approx 1.26$, Eqs. (26), (27), and (28) reduce to

$$\Phi_{2,\text{best}} = 0.345\sigma'^{1/2} A^{-1} \tag{30}$$

$$X_{2,\text{best}} = \pm 0.332A(2.9\sigma'^{-1/2}A - 1)^{-1/2} \tag{31}$$

$$|\Delta_2'|_{\max} = 0.164\sigma'^{-1/2} \tag{32}$$

It is very interesting to observe from Eqs. (31) and (32) that the same degree of maximum separations are obtained, either cold tube rotated or hot tube rotated. Consequently, the plus and minus signs in Eq. (31) may be omitted. Since $\Phi_{2,\text{best}} \leq 1$ in Eq. (30), or $(2.9\sigma'^{-1/2}A - 1) \geq 0$ in Eq. (31),

$$\sigma' \leq 8.4A^2 \tag{33}$$

which should be satisfied if Eqs. (31) and (32) are to have solutions.

WIRED COLUMN WITH STATIONARY TUBES

When wired columns are operated with stationary tubes, the effect of fluid shear vanishes and only the wire angle of inclination plays the role of reducing the remixing effect. The equation of separation can be obtained from Eq. (1) or Eq. (25) by setting $X = 0$:

$$\Delta_3' = \frac{A\Phi}{4\sigma'}\left[1 - \exp\frac{-\sigma'}{A^2\Phi^2 + \Phi}\right] \tag{34}$$

The best wire angle of inclination and maximum separation were given by Yeh, Ward, and Ho (*9, 14*):

$$\Phi_{3,\text{best}} = \frac{-1 + \sqrt{1 + 4A^2\sigma'/y}}{2A^2} \tag{35}$$

$$\Delta_{3,\text{best}}' = \frac{-1 + \sqrt{1 + 4A^2\sigma'/y}}{8\sigma' A}(1 - e^{-y}) \tag{36}$$

in which y is determined from

$$e^y = 1 + 2y + \frac{y^2(1 - \sqrt{1 + 4A^2\sigma'/y})}{2A^2\sigma'} \tag{37}$$

From Eq. (37) we also get $y \approx 1.26$, and Eqs. (35) and (36) reduce to

$$\Phi_{3,\text{best}} = 0.89\sigma'^{1/2}A^{-1} \tag{38}$$

$$\Delta_{3,\max}' = 0.16\sigma'^{-1/2} \tag{39}$$

with the restriction

$$\sigma' \leq 1.26A^2 \tag{40}$$

COMPARISON OF SEPARATION

When an open column (the column without a wire spiral) with a stationary tube is considered, $X = 0$ and $\Phi = 1$, and either Eq. (1), or Eq. (25), or Eq. (34) reduces to

$$\Delta_0' = \frac{A}{4\sigma'}\left[1 - \exp\frac{-\sigma'}{A^2+1}\right] \tag{41}$$

Yeh and Ward (*9*) pointed out that the separation efficiency of a concentric-tube thermal diffusion column can be improved by means of a wire spiral having a diameter equal to the annular spacing and inserted as a spacer in the annular region when $\sigma' \leq 1.26A^2$, i.e., $\Delta_{3,\max}' > \Delta_0'$. Later, Yeh and Ho (*14*) showed that further improvement in separation was obtained by rotating the tubes oppositely in a wired concentric-tube column when $\sigma' \leq 0.42A^2$, i.e., $|\Delta_1'|_{\max} > \Delta_{3,\max}' > \Delta_0'$. From Eqs. (16), (32), and (39) we then conclude that

$$|\Delta_1'|_{\max} > |\Delta_2'|_{\max} > \Delta_{3,\max}' > \Delta_0', \qquad \sigma' \leq 0.42A^2 \tag{42}$$

It is difficult to put $|\dot{\Delta}_1'|_{\max}, |\Delta_2'|_{\max}$, $\Delta_{3,\max}'$ and Δ_0' in order for $\sigma' > 0.42A^2$ because obviously the magnitude of $|\Delta_1'|_{\max}$ cannot be compared with those of others by using Eq. (22). However, comparison can be made successfully by graphical representation as shown in Fig. 3. The results are

$$|\Delta_1'|_{\max} > |\dot{\Delta}_1'|_{\max} > |\Delta_2'|_{\max} > \Delta_{3,\max}' > \Delta_0', \; 0.42A^2 > \sigma' \geq \frac{y\Phi^2}{28}A^2 \tag{43}$$

and

$$|\dot{\Delta}_1'|_{\max} > |\Delta_2'|_{\max} > \Delta_{3,\max}' > \Delta_0', \qquad \sigma' > 0.42A^2 \tag{44}$$

Consequently, considerable improvement in separation is still obtainable in the wired column with tubes rotated oppositely at the best speed, even under higher flow-rate operations, i.e., $\sigma' > 0.42A^2$.

It is evident from Fig. 3 that $|\dot{\Delta}_1'|_{\max}$ increases as Φ does. However, this also increases $\dot{X}_{1,\text{best}}$ as shown in Fig. 2 and thereby leads to raising the operating cost. For the extreme case that Φ approaches unit, $\dot{X}_{1,\text{best}}$ as well as $V_{1,\text{best}}$ approaches infinity, as shown by Eq. (18). On the other hand, since all separation theories of wired columns were derived under the assumption that the space occupied by the wire spiral in the annulus is negligible, the separation equations become increasingly inaccurate as Φ decreases, and cannot be applied when Φ approaches zero because the annular space is occupied entirely by the wire spiral at that time.

The improvement in separation by operating at the optimal conditions is best illustrated by calculating the percentage increase in separation based on an open column with stationary tubes:

$$I = \frac{\Delta_{max} - \Delta_0}{\Delta_0} \tag{45}$$

For the purpose of illustration, let us extend the numerical example given in Yeh and Ho's work (*14*). The results are presented in Table 1, in which the values of $\phi_{1,best}$ have been corrected. The mistakes in the previous paper were due to calculation errors. It is also shown in Table 1 that $\sigma'/y\Phi = 5 \times 10^3$ to 2.6×10^5 and $\sigma'/y^2\Phi = 4.7 \times 10^3$ to 2×10^5. Therefore, the assumptions that $\sigma'/y\Phi \gg 1$ and $\sigma'/y^2\Phi \gg 1$ are reasonable.

CONCLUSIONS

It has been shown that the cascading effect in wired concentric-tube thermal diffusion columns can be effectively improved even for higher flow-rate operations, $\sigma'/A > 0.42$. The equations of optimal conditions and maximum separation have been derived. From these equations and the given example, we conclude that

$$|\Delta_1|_{max} > |\Delta_2|_{max} > \Delta_{3,max} > \Delta_0 \qquad \text{for} \qquad \sigma' \le 0.42A^2$$

and

$$|\dot{\Delta}_1|_{max} > |\Delta_2|_{max} > \Delta_{3,max} > \Delta_0 \qquad \text{for} \qquad \sigma' > 0.42A^2$$

Therefore, in order to obtain a higher degree of separation, the use of a wire column with the tubes rotated oppositely, operating at the best tube-speed of rotation, and the best wire angle of inclination (Column I), is recommended for $\sigma'/A^2 \le 0.42$, there is no best wire angle of inclination for a rotated column. However, for flow rates that exceed this critical value, the degree of separation obtainable in a wired column, with the tube rotated oppositely and operating at the best tube speed of rotation (Column I′), is still higher than those obtainable in other types of concentric-tube columns.

TABLE 1
Comparison of Separation Obtained in Various Types of Columns

		Open column with stationary tubes,	Wired column with stationary tubes			Wired column with one tube rotated			
$\sigma \times 10^3$ (g/s)	$\sigma'(A^{-2})$	Δ_0 (%)	$\phi_{3,best}$ (degrees)	$\Delta_{3,max}$ (%)	I_3 (%)	$\phi_{2,best}$ (degrees)	$V_{2,best}$ (cm/s)	$\|\Delta_2\|_{max}$ (%)	I_2 (%)
1	0.0364	10.1	65.6	34.6	242.5	75.1	0.198	35.6	252.5
2	0.0728	9.9	60.6	24.5	150.5	72.2	0.239	25.1	153.5
4	0.1456	9.5	54.2	17.4	83.1	68.7	0.291	17.8	87.4
16	0.5824	7.8	34.4	8.7	11.5	59.1	0.447	8.9	14.1
64	2.3296	4.0	—	—	—	43.4	0.789	4.5	12.5

		Wired column with tube rotated and $\phi = 45°$					Wired column with tubes rotated oppositely			
$\sigma \times 10^3$ (g/s)	$\sigma'(A^{-2})$	$\dot{V}_{1,best}$ (cm/s)	$\|\dot{\Delta}_1\|_{max}$ (%)	$\dot{I}_1$ (%)	$\sigma'/y\Phi$	$\sigma'/\Phi y^2$	$V_{1,best}$ (cm/s)	$\phi_{1,best}$ (degrees)	$\|\Delta_1\|_{max}$ (%)	I_1 (%)
1	0.0364	0.64	38.9	285.0	4,990	4,692	0.48	57.0	39.8	294.1
2	0.0728	0.70	28.2	184.8	8,748	7,210	0.63	49.6	28.2	184.8
4	0.1456	0.80	20.0	110.0	16,620	12,976	0.89	39.5	20.0	110.0
16	0.5824	1.13	9.8	25.6	65,352	50,159	—	—	—	—
64	2.3296	1.18	4.8	20.0	264,391	205,241	—	—	—	—

Consequently, Column $\dot{I}$ is recommended for use under higher flow-rate operations.

The degree of separation obtainable in Column $\dot{I}$ is affected by the wire angle of inclination. Decreasing the inclination of the wire angle (or increasing Φ) in Column $\dot{I}$ will increase the degree of separation. Unfortunately, this also leads to increasing the best tube speed of rotation and thereby raising the operating cost. Therefore, the economic factors concerning the best tube speed of rotation and the maximum separation obtainable must be taken into consideration simultaneously when Column $\dot{I}$ is employed.

The equation of separation for wired thermal diffusion columns with only one tube rotated (Column II) has also been derived. Accordingly, the maximum separation and the best tube speed of rotation, as well as the best inclination of the wire angle, are then obtained. Although considerable improvement in separation was also obtained in Column II as compared with a stationary open column and even with a stationary wired column, the degree of separation in such a column is lower than those obtainable in Columns I and $\dot{I}$.

SYMBOLS

A	system constant defined by Eq. (9)
B	wire spacing of wired concentric-tube column, i.e., $B = 2\pi R_1 \cos \phi$
c_B, c_T	fractional mass concentration of Component 1 in the product stream exiting from the stripping, enriching section
D	ordinary diffusion coefficient
g	gravitational acceleration
H_0	system constant defined by Eq. (2)
h	height of concentric-tube column
I	improvement in separation defined by Eq. (45)
K_d, K_0	system constants defined by Eqs. (4), (3)
L	length of transport path
R_1	outside radius of inner tube of concentric-tube columns
R_2	inside radius of outer tube of concentric-tube columns
$\overline{T}$	absolute reference temperature
T_1, T_2	temperature of cold, hot wall
V	tangential velocity of the rotating tubes
V_{best}	best value of V for maximum separation
X	dimensionless velocity defined by Eq. (5)
X_{best}	best value of X for maximum separation

Greek Letters

α	thermal diffusion constant
$\overline{\beta}_T$	$-(\partial\rho/\partial T)_p$ at $\overline{T}$
Δ	$C_T - C_B$
Δ_0	Δ obtained in open column with stationary tubes
Δ_1	Δ obtained in wired column with tubes rotated in opposite direction
Δ_1'	Δ_1 obtained under higher flow-rate operations
Δ_2	Δ obtained in wired column with one tube rotated
Δ_3	Δ obtained in wired column with stationary tubes
Δ_{max}	Δ obtained under the optimal operating conditions
Δ'	reduced separation defined by Eq. (8)
ΔT	$T_2 - T_1$
Φ	$\cos^2 \phi$
Φ_{best}	best value of Φ for maximum separation
ϕ	wire angle of inclination from the vertical
ϕ_{best}	best value of ϕ for maximum separation
μ	viscosity
$\overline{\rho}$	mass density at $\overline{T}$
σ	mass flow rate in the enriching or stripping section

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