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

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NOTE

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HO-MING YEH

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

Abstract

It has been found that the maximum separation obtainable in inclined thermal diffusion columns is proportional to the square root of plate spacing when the operating expense is fixed. The plate spacing is generally so small that changing it, as well as changing the angle of inclination, may not cause additional fixed charge. However, increasing the plate spacing will lead to increasing the difference of plate temperatures in order to keep the operating expense unchanged. Therefore, additional cost is needed to maintain a high value of temperature difference.

INTRODUCTION

Thermogravitational thermal diffusion columns have been used to bring about separation in both gas and liquid solutions. Although application of the thermal diffusion separation process has been limited by its high heat requirement, the process can be applied to the separation of highly valuable materials such as isotopes and rare gases which are difficult or impossible to separate by other means.

Recently, several improved columns (*5–11, 13, 17–19*) have been developed to increase the separation efficiency and thereby lead to decreasing the heat requirements. In developing these improved columns, a number of studies of the operating variables in the thermal diffusion column have been made. There is still an important term, plate spacing, which affects

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separation efficiency and which has not been discussed. It is the purpose of this work to investigate the effect of plate-spacing changes on the degree of separation of an inclined thermal diffusion column when the operating expense is fixed.

COLUMN THEORY

Jones, Furry, and Onsager (*2–4*) gave an excellent treatment of column theory. They presented the equation of separation for a thermal diffusion column in continuous operations, with the binary feed introduced at the middle of the column, with top and bottom products withdrawn at the same rates. The equation of separation is

$$\Delta = \frac{H}{2\sigma}\left[1 - \exp\left(-\frac{\sigma L}{2K}\right)\right] \tag{1}$$

where

$$H = \frac{\alpha\rho\beta_T g \cos\theta\,(2\omega)^3 B(\Delta T)^2}{6!\mu \mathrm{T}} \tag{2}$$

$$K = K_c + K_d \tag{3}$$

$$K_c = \frac{\rho\beta_T^2 g^2 \cos\theta\,(2\omega)^7 B(\Delta T)^2}{9!D\mu^2} \tag{4}$$

$$K_d = 2\omega BD\rho \tag{5}$$

The most important assumption in their work is that the concentration in the column is anywhere between 0.3 and 0.7 weight fraction. Also, only moderate flow rates are considered. For operations at high flow rates and in the whole range of concentrations, some suitable corrections are necessary, as shown by Powers and Wilker (*6*) and Yeh et al. (*12, 14–16, 20*).

THE BEST ANGLE OF INCLINATION FOR MAXIMUM SEPARATION

Since the system constants, H and K, possess high power terms of ω, it plays an important role in separation efficiency in the separation equation. The plate spacing in a thermal diffusion column is generally so small that changing 2ω, as well as changing θ, will not cause any additional fixed charge. The expenditure of making a separation by thermal diffusion essentially includes two parts: a fixed charge and an operating expense. The fixed charge is roughly proportional to the equipment cost, while the operating expense is chiefly heat. The heat transfer rate is obtainable from $kBL(\Delta T)/2\omega$. By using these terms, we shall take account of the influence of both plate spacing and inclined angle on the degree of separation when the operating expense is fixed. Therefore, Eq. (1) can be rewritten as

$$\Delta = \frac{a(2\omega)^5 \cos\theta}{2\sigma}\left[1 - \exp\frac{-\sigma L}{2\{b_1(2\omega)^9 \cos^2\theta + b_2(2\omega)\}}\right] \tag{6}$$

where

$$a = \frac{\alpha\rho\beta_T g B(\Delta T/2\omega)^2}{6!\mu T} = \text{constant} \tag{7}$$

$$b_1 = \frac{\rho\beta_T^2 g^2 B(\Delta T/2\omega)^2}{9!D\mu^2} = \text{constant} \tag{8}$$

$$b_2 = \rho BD = \text{constant} \tag{9}$$

The best angle of inclination for maximum separation is obtained by partially differentiating Eq. (6) with respect to θ and setting $\partial\Delta/\partial(\theta) = 0$. After differentiation and simplification we obtain

$$\exp\left[\frac{\sigma L}{2\{b_1(2\omega)^9 \cos^2\theta^* + b_2(2\omega)\}}\right] = 1 + \frac{\sigma L\{b_1(2\omega)^9 \cos^2\theta^*\}}{\{b_1(2\omega)^9 \cos^2\theta^* + b_2(2\omega)\}^2} \tag{10}$$

Define

$$y = \frac{\sigma L}{2\{b_1(2\omega)^9 \cos^2\theta^* + b_2(2\omega)\}} = \frac{\sigma'}{\dfrac{b_1}{b_2}(2\omega)^8 \cos^2\theta^* + 1} \tag{11}$$

and

$$\sigma' = \frac{\sigma L}{2b_2(2\omega)} \tag{12}$$

Equation (10) becomes

$$e^y = 1 + 2y - 2y^2/\sigma' \tag{13}$$

Generally, $\sigma' > 100$, and the last term on the right-hand side of Eq. (13) may be neglected. Thus, $y = 1.26$, and from Eq. (11):

$$\cos^2 \theta^* = \left(\frac{\sigma'}{1.26} - 1\right) / \frac{b_1(2\omega)^8}{b_2} \doteq \frac{b_2\sigma'}{1.26(2\omega)^8 b_1} \tag{14}$$

$$\theta^* = \cos^{-1} \sqrt{\frac{\sigma L}{2.52 b_1(2\omega)^9}} \tag{15}$$

Consequently, the maximum separation may be obtained from Eq. (6) by substitution of Eq. (15). The result is

$$\Delta_{max} = 0.226a \left[\frac{L(2\omega)}{b_1\sigma}\right]^{1/2} \tag{16}$$

THE EFFECT OF PLATE SPACING ON THE DEGREE OF SEPARATION

Chueh and Yeh (1) gave the maximum separation in an inclined thermal diffusion column without operating expense fixed as

$$\dot{\Delta}_{max} = 0.226 \left(\frac{H_0^2 L}{K_0 \sigma}\right)^{1/2} \tag{17}$$

in which

$$H_0 = H/\cos \theta \tag{18}$$

$$K_0 = K/\cos^2 \theta \tag{19}$$

It is evident from Eq. (17) that

$$\dot{\Delta}_{max} \propto 1/\sqrt{2\omega} \qquad (20)$$

Thus, decreasing the plate spacing leads to increasing the maximum separation, and also to increasing the operating expense.

However, because the operating expense is fixed, the relation between plate spacing and the maximum separation is obtained from Eq. (16) as

$$\Delta_{max} \propto \sqrt{2\omega} \qquad (21)$$

In this case, increasing the plate spacing will increase the maximum separation with the operating expense unchanged.

A comparison of maximum separation may be made by using the experimental data of Chueh and Yeh's work (*1*). Materials: benzene and *n*-heptane; $\Delta T = 164 - 95 = 69°F = 38.3°C$; $2\omega = 0.09$ cm; $L = 185$ cm, $H_0 = 0.845$ g/min; $K_0 = 419$ g·cm/min. If the operating expense is unchanged, i.e., $\Delta T/(2\omega) = 38.3/0.09$ (°C/cm), then

$$a = \frac{H_0}{(2\omega)^5} = \frac{0.845}{(0.09)^5} = 1.433 \times 10^5 \text{ g/(cm)}^5\text{(min)}$$

$$b_1 = \frac{K_0}{(2\omega)^9} = \frac{419}{(0.09)^9} = 1.08 \times 10^{12} \text{ g/(cm)}^8\text{(min)}$$

Consequently, the maximum separation and the best angle of inclination of various plate spacing are calculated from Eqs. (15) and (16), and the results are presented in Table 1. In Table 1, the improvement of separation is defined as

$$I = \frac{\Delta_{max} - \Delta_0}{\Delta_0} \qquad (22)$$

CONCLUSION

The effect of plate spacing on the separation efficiency of inclined flat-plate thermal diffusion columns has been investigated. It has been found that the maximum separation of an inclined column is proportional to the square root of 2ω when the operating expense is fixed. The plate spacing in a thermal diffusion column is generally so small that changing 2ω, as well as

TABLE 1
Comparison of Separation Obtained at Various Plate Spacing

	$2\omega = 0.09$ cm, $\Delta T = 38.3°C$				$2\omega = 0.12$ cm, $\Delta T = 51.1°C$			$2\omega = 0.15$ cm, $\Delta T = 63.9°C$		
σ (g/min)	Δ_0 (%)	θ^* (deg)	Δ_{max} (%)	I (%)	θ^* (deg)	Δ_{max} (%)	I (%)	θ^* (deg)	Δ_{max} (%)	I (%)
0.49	8.9	73.0	18.2	105	85.4	21.0	135	88.3	23.5	158
0.98	8.4	65.5	12.8	52	83.5	14.8	76	87.6	16.5	96
1.96	7.6	54.3	9.1	20	80.8	10.5	38	86.6	11.7	54

changing θ, will not cause any additional fixed charge. However, increasing 2ω will lead to increasing ΔT in order to maintain $\Delta T/2\omega$ constant, and, therefore, some additional cost is needed to maintain the higher ΔT. Table 1 shows an example of the improvement of maximum separation obtained by increasing the plate spacing. It is evident that ΔT must be kept as high as 63.9°C when the plate spacing is 0.15 cm. Since the boiling points of both benzene and *n*-heptane are about 80°C, the temperature of the cold plate of a thermal diffusion column must be held as low as 0°C. In this case, although the heat transfer rate is still the same, kBL (38.3/0.09), some additional expense is needed to keep the cold plate as low as 0°C.

SYMBOLS

a	system constant defined by Eq. (7)
B	column width
b_1, b_2	system constant defined by Eq. (8), Eq. (9)
D	ordinary diffusion coefficient
g	gravitational acceleration
H	system constant defined by Eq. (2)
H_0	$H/\cos\theta$
I	improvement of separation defined by Eq. (21)
K	system constant defined by Eq. (3)
k	thermal conductivity
K_0	$K/\cos^2\theta$
L	column length
T	absolute temperature
T_1, T_2	temperature of hot, cold wall
ΔT	$T_1 - T_2$
$\bar{T}$	reference temperature
y	dimensionless group defined by Eq. (11)

Greek Letters

α	thermal diffusion constant
β	$-(\partial\rho/\partial T)_{\bar{T}}$
Δ, $\dot{\Delta}$	difference of mass fraction of Component 1 between top and bottom products in inclined column with, without operating expense fixed
Δ_{max}, $\dot{\Delta}_{max}$	maximum value of Δ, $\dot{\Delta}$
Δ_0	Δ obtained in vertical column
μ	viscosity of fluid
θ	angle of inclination of column plate from the vertical
θ^*	angle of inclination for best performance
ρ	mass density
σ	mass flow rate
σ'	$\sigma L/2b_2(2\omega)$
ω	one-half of the plate spacing of the column

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