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DESIGN OF PERIODIC-ACTION THERMAL DIFFUSION COLUMNS WITH BAFFLES

G. I. Bobrova and G. D. Rabinovich

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Presented is a method of designing thermal diffusion columns with baffles. Recommendations are made concerning the choice of optimal conditions and improved separation efficiency.

In [1] the authors presented the results of experimental studies on the intensification of thermal diffusion separation in liquids by insertion of a perforated baffle at the interface between the two convective streams.

As a consequence of the difference in the specific gravity of the liquid on either side of the baffle, circulation develops in the column, the driving head

$$\Delta P = L(\gamma_1 - \gamma_2) \tag{1}$$

being spent in overcoming the resistance to the motion of the two streams, i.e.,

$$L(\gamma_1 - \gamma_2) = \frac{\lambda_1 L}{d'_{\text{eff}}} \frac{v_1^2}{2g} \gamma_1 + \frac{\lambda_2 L}{d''_{\text{eff}}} \frac{v_2^2}{2g} \gamma_2, \tag{2}$$

where the subscript 1 and the single prime relate to the cooler stream. For laminar flow in a flat narrow channel

$$\lambda = 96/\text{Re}. \tag{3}$$

If the baffle is located an equal distance δ from the cold and hot surfaces, then $d'_{\text{eff}} = d''_{\text{eff}} = d_{\text{eff}}$; moreover, because of the small difference in density between the two streams, one can assume that $v_1 = v_2 = v$.

Thus, from (1), (2), and (3) we obtain

$$v = \frac{g\delta^2}{24} \frac{\rho_1 - \rho_2}{\eta}, \tag{4}$$

where $\eta = (\eta_1 - \eta_2)/2$, while the values of the physical constants must be determined from the mean temperature of each stream, i.e.,

$$\begin{aligned} \bar{t}_1 &= t_1 + \frac{\delta/\lambda_l}{2[2\delta/\lambda_l + (\delta_0 - 2\delta)/\lambda_b]}(t_2 - t_1); \\ \bar{t}_2 &= \frac{1}{2}(t_1 + t_2) + \frac{(\delta_0 - 2\delta)/\lambda_b + \delta/\lambda_l}{2[2\delta/\lambda_l + (\delta_0 - 2\delta)/\lambda_b]}(t_2 - t_1). \end{aligned} \tag{5}$$

The basis of the proposed method of analyzing the operation of columns with baffles is the theory of thermal diffusion columns presented in [2], with a number of changes connected with the special features of the new method.

Firstly, the expression for the transverse flow of enriched component is modified by introducing a multiplier ξ, which allows for transverse mixing due to interaction of the streams; thus

$$j_x = \xi\rho D\left(\sigma c_1 c_2 \frac{\Delta T}{\delta_0} - \frac{c_1^{II} - c_1^{I}}{\delta_0 - \delta}\right). \tag{6}$$

The quantity ξ may take different values depending on the degree of mixing; for turbulent flow obviously $\xi = 0$. The transport equation remains unchanged:

$$j = Hc(1 - c) - (K_c + K_d)\,dc/dz. \tag{7}$$

The constants H, K_c, and K_d assume a somewhat different form:

$$H = \sigma \rho v \delta \Delta T B (1 - \delta/\delta_0), \tag{8}$$

$$K_c = \frac{1}{\xi D} \rho \delta^2 \delta_0 v^2 B (1 - \delta/\delta_0), \tag{9}$$

$$K_d = 2\rho\delta DB. \tag{10}$$

From (9) and (10) we obtain the ratio

$$\frac{K_c}{K_d} = \frac{1}{2\xi}\left(1 - \frac{\delta}{\delta_0}\right)\frac{\delta v}{D}\,\frac{\delta_0 v}{D} = \frac{1}{2\xi}\left(1 - \frac{\delta}{\delta_0}\right) \mathrm{Pe}\,\mathrm{Pe}_0. \tag{11}$$

Since in liquids the Pe number is of the order $10^2 - 10^3$, while the quantity ξ, as will be shown below, is of the order of tens, the ratio given by (11) is large, so that in (7) the quantity K_d can be disregarded in comparison with K_c.

Consequently, in contrast to gases, the ratio (11) cannot be employed as a measure of the hydrodynamic stability of the flow.

Using (4), we determine the quantity

$$2A = \frac{H}{K_c} = \frac{\sigma \Delta T D \xi}{\delta \delta_0 v} = \frac{24}{g}\,\frac{\sigma \eta D \Delta T \xi}{\delta_0 \delta^3 (\rho_1 - \rho_2)}, \tag{12}$$

which is of great significance in determining the efficiency of a column. As may be seen from (12), for fixed values of σ, η, D, δ_0, δ, ΔT the quantity 2A depends mainly on the difference in density, which in its turn is determined by the temperature difference $\bar{t}_2 - \bar{t}_1$.

$$\bar{t}_2 - \bar{t}_1 = \frac{\delta/\lambda_l + (\delta_0 - 2\delta)/\lambda_b}{2\delta/\lambda_l + (\delta_0 - 2\delta)/\lambda_b}\,(t_2 - t_1). \tag{13}$$

Obviously, the greater the thermal conductivity of the baffle, the less the temperature difference and density difference and, consequently, the greater the separation coefficient, given in the stationary state by the expression

$$q_e = \exp(2AL). \tag{14}$$

The second change in the formulas presented in [2] consists in the definition of the column length L that participates in the separation.

In the usual thermal diffusion column L is the length over which cross transfer due to thermal diffusion is realized, i.e., in practice the height of the column. In the presence of a baffle, contact between the two streams is realized through the perforations, and it is obvious that the geometric height of the column L is not equal to the length L_{eff}, over which the streams interact; in fact, $L_{eff} < L$. The effective length is given by the relation $L_{eff} = \phi L$, where ϕ is the clear cross section of the baffle. Thus, the basic formulas presented in [2] can also be applied to columns with perforated baffles.

For columns, in which a constant concentration is maintained at one end, the change of the separation factor with time is given by the relation

$$\frac{q - 1}{q_e - 1} = 1 - \exp(-\tau/\tau_r), \tag{15}$$

$$\tau_r = \frac{\mu}{2AH}\left(\exp(2AL_{eff}) - 2AL_{eff} - 1\right).$$

Bearing in mind that $\mu = 2\rho\delta B$, we obtain, using (8) and (12),

$$\tau_r = \frac{2\delta\delta_0}{\xi D (\sigma \Delta T)^2 (1 - \delta/\delta_0)}\left[\exp(2AL_{eff}) - 2AL_{eff} - 1\right]. \tag{16}$$

From an examination of (16) it is clear that the relaxation time can be calculated if the quantity ξ is known. The latter, however, can be determined only by experiment, since it is expressed by a combination of hydrodynamic factors, causing mixing of the streams, i.e., factors whose theoretical quantitative evaluation, in the light of the present state of our knowledge of the hydrodynamic motion of liquids in narrow channels, is virtually impossible.

It is extremely probable that $\xi = f(d_b/\delta_{per})$, but it is not excluded that the rate of mixing also depends on the temperature difference ΔT and on the physical properties of the liquid, i.e., that ξ is expressed by the relation

$$\xi = A\,[(\mathrm{Gr})\,(d_b/\delta_{per})]^{-m}\,.$$

An experimental study, reported in [1], has been carried out with sucrose solutions, whose initial concentration ($c_0 = 2.7\%$) was maintained constant at the top of the column.

In the series of experiments in question $\delta_0 = 0.86$ mm, $\delta = 0.28$ mm, $t_1 = 30°C$, $t_2 = 50°C$.

Bearing in mind that a dilute solution of sucrose was used, the density and viscosity were determined as for pure water. For the Soret and concentration diffusion coefficients, in calculations based on our experiments and those of other authors [3, 4], we took the values of $2 \cdot 10^{-3}$ deg^{-1} and $5 \cdot 10^{-6}$ cm^2/sec, respectively. The thermal conductivity of the baffle was found experimentally to be 0.232 W/m·deg.

The aim of the calculation was to find the value of the coefficient ξ which best approximates the experimental data.

Figure 1 shows the calculated curves and experimental points. The deviation from the experimental points is due to the frequent sampling, which upset the normal concentration distribution in the column.

The values of ξ obtained are shown in Fig. 2 as a function of the ratio of the diameter of the perforations to the thickness of the baffle. Notice the sharp growth of ξ with decrease of this ratio. The ratio d_b/δ_{per} was chosen as argument because the mixing action connected with penetration of one stream into the other, is determined not only by the diameter of the perforations, but also by the thickness of the baffle; the thicker the latter, the more difficult the hydrodynamic interaction of the streams. However, this statement requires experimental verification.

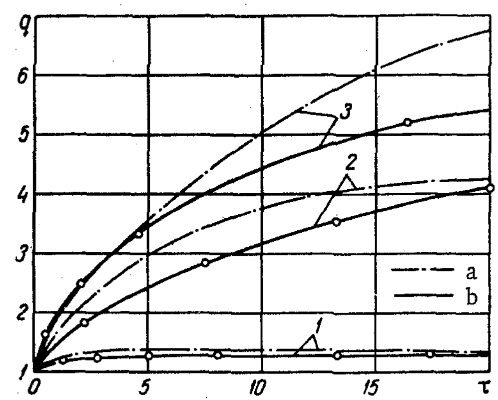

Fig. 1. Change in concentration of sugar at bottom of column and dependence on time for a wall temperature difference of 19.6°C: a) experimental data; b) curve calculated from (15); 1) clear cross section of baffle 22.8%, perforation diameter 5 mm; 2) 19%, 3.5 mm; 3) 22%, 2 mm.

On the basis of the experimental data obtained, a number of recommendations may be made with a view to increasing the efficiency of separation in columns with baffles.

Denoting the equilibrium separation coefficients for columns with and without a baffle by q_e and q_e' and taking into consideration (14), (12), we obtain

$$\frac{\ln q_e}{\ln q_e'} = 2\xi\,\frac{\delta\,(\rho_1' - \rho_2')}{\delta_0\,(\rho_1 - \rho_2)}\,\frac{L_{eff}}{L}. \tag{17}$$

For purposes of engineering calculations it is useful to consider the following recommendations.

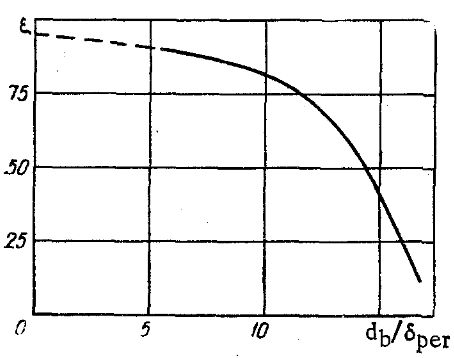

Fig. 2. Dependence of ξ on the ratio of perforation diameter to baffle thickness.

1. It is desirable to enlarge the effective length of the column.

2. One should try to reduce the density difference between streams. Thus, for example, in our experiments using steel instead of rubberized fabric as baffle material should halve this difference.

3. The ratio of the linear dimension of the perforation in the direction of motion of the stream to the thickness of the baffle must be a minimum. Calculations show that with a correct choice of baffle parameters it is easy to attain ratios of the logarithms of the separation coefficients of the order of several tens.

In conclusion, it must be pointed out that in the separation of liquids differing appreciably in specific gravity the solution leading to (15) must be corrected by taking account in the initial equation

$$\mu \frac{\partial c}{\partial \tau} = -\operatorname{div} j$$

of the dependence of density on concentration.

NOTATION

L—length of column; γ_1 and γ_2—specific gravity of liquid in descending and ascending streams; $\lambda_{1,2}$—coefficients; v—velocity of liquid in ascending or descending stream; η—dynamic viscosity; $\overline{t}_1$—mean temperature of descending stream; t_1—temperature of cold wall; λ_l—thermal conductivity of liquid; λ_b—thermal conductivity of baffle; t_2—temperature of hot wall; $\overline{t}_2$—mean temperature of ascending stream; ξ—coefficient describing transverse mixing due to interaction of streams; σ—Soret coefficient; ΔT—wall temperature difference; D—concentration diffusion coefficient; ρ—density; τ—relaxation time; B—width of column; μ—mass of component per unit length of column.

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Institute of Heat and Mass Transfer, AS BSSR, Minsk