USE OF SYSTEMS WITH CENTRAL FEED AND COUNTERFLOW IN THERMODIFFUSION UNITS TO CLEAN FLUIDS

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A determination is made of the parameters necessary to evaluate the efficiency of different systems for cleaning fluids in thermodiffusion units.

Methods used to analyze the efficiency of equipment for separating mixtures of liquids or gases should be based [1, 2] on a consideration of the cost of the equipment, energy, coolant, and feed and expenditures on servicing and repair. When evaluating the effect of these factors on the total cost, it is necessary to know the working surface per unit of product obtained per unit to time. Here we present a method of calculating this characteristic and we show its relationship with other parameters for the systems represented in Fig. 1.

We will examine the case of the purification of a mixture when the concentration of the main component is close to unity and the content of the impurity is low and $c(1 - c) \approx (1 - c)$. We have the following in this case for the degree of separation

$$q_e = \frac{1 - c_0}{1 - c_e}, \quad q_i = \frac{1 - c_i}{1 - c_0}, \tag{1}$$

while the balance relations can be written in the form

$$\sigma_0 = \sigma_p + \sigma_i, \tag{2}$$

$$\sigma_0 = \sigma_p \frac{1}{q_e} + \sigma_i q_i. \tag{3}$$

Below, we will assume that the total amount of mixture σ_0 entering the unit is constant and we will use the ratio of the product stream to the total amount of mixture

$$k \equiv \frac{\sigma_p}{\sigma_0} = \frac{1 - q_i}{1 - q_i q_e} q_e. \tag{4}$$

The productivity σ_p and the coefficient k, according to (4), take maximum values $\sigma_p{}^*$ and k^* at the maximum degree of separation $q_i{}^*$, in accordance with the condition of equilibrium ($\tau = 0$) of the feed and product streams.

The analysis is simplified considerably if, following [4], we introduce the ratio of the actual productivity to the maximum productivity and the degree of approach of the concentration in the spent material to the equilibrium concentration

$$\theta \equiv \frac{\sigma_p}{\sigma_p^*} = \frac{k}{k^*}, \quad \Psi \equiv \frac{q_i^* - q_i}{q_i - 1}. \tag{5}$$

In accordance with (4) and (5), $\sigma_i = \sigma_p[(1 - \theta k^*)/\theta k^*]$.

It is known [3-5] that the most suitable operating regime for the scheme in Fig. 1a is a regime in which the concentrations of the components in the original mixture and at the point of entry are equal. The expressions for the degree of separation at the outlet of the column are as follows in this case [5]:

$$q_e = \frac{\varkappa_e - \exp[(1 - \varkappa_e)(y_e - y_0)]}{\varkappa_e - 1}, \tag{6}$$

$$q_i = \frac{\varkappa_i - 1}{\varkappa_i + \exp[-(1 + \varkappa_i) y_0]} \tag{7}$$

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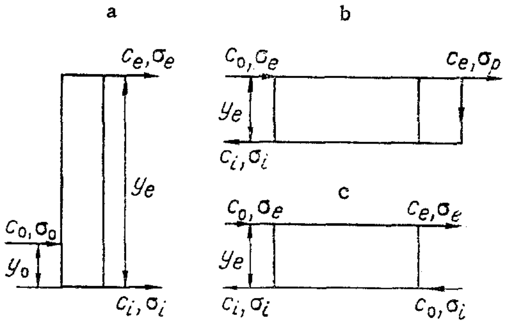

Fig. 1. Schemes for feed and removal of a mixture in thermodiffusion units: a) feed into the middle part of the column; b) reflux with partial return of the mixture; c) reflux.

and are connected with the balance relation (3). Meanwhile, in the case being examined, $\sigma_p = \sigma_e$. Insertion of Eqs. (6) and (7) into (3) gives

$$q_e q_i = \exp\left[y_e - \varkappa_e \left(y_e - \frac{y_0}{k} \right) \right]. \tag{8}$$

With allowance for Eqs. (6) and (5), Eqs. (8) give us an expression for the parameter $y_e/\varkappa_p$, which determines the working surface per unit of product removed per unit of time:

$$\frac{y_e}{\varkappa_p} = \frac{y_e - (y_0/\theta k^*)}{1 - \frac{1}{y_e} \ln\left(\frac{q_e - k^*\theta}{1 - k^*\theta} \right)}. \tag{9}$$

For the scheme in Fig. 1a, the maximum degree of separation on the basis of the equilibrium condition is $q_i^* = \exp(y_0)$.

Simultaneous solution of Eqs. (6) and (9) for y_0 and $\varkappa_e$ makes it possible to obtain the quantity $y_e/\varkappa_p$ for different values of q_e, y_e, and k. The results of calculations show that the working surface per unit of product in the case being considered decreases with an increase in the parameter y_e and has a minimum at $y_e = y_{eopt}$. The value of y_{eopt} depends on the parameter k, which determines the ratio of the product stream to the total amount of mixture entering the unit. Figure 2 shows the dependence of y_{eopt} on k and the corresponding values of $y_e/\varkappa_p$ at different values of q_e. The dependence of the coordinate of the point of entry of the initial mixture y_0 on k is shown only for $q_e = 100$ (the position of the point of entry can be considered nearly independent of q_e).

It is interesting to perform similar calculations for a reflux unit without closure of the flows (Fig. 1c). In accordance with [5], we write the following for the degree of separation at the outlet in this case

$$\frac{1}{q_e} = 1 + \frac{(1 - \exp(-y_e))(\exp\varphi - 1)\left(1 - \left(\frac{1}{\varphi\varkappa_i} + 1 \right)\exp(-y_e) \right)}{1 - \left(\frac{1}{\varphi\varkappa_i} + 1 \right)\exp(-y_e) + \frac{1}{\varphi\varkappa_i}\exp(\varphi - y_e)}, \tag{10}$$

$$q_i = 1 - \frac{1}{\varphi\varkappa_i} \frac{(1 - \exp\varphi)(1 - \exp(-y_e))}{1 - \left(\frac{1}{\varphi\varkappa_i} + 1 \right)\exp(-y_e) + \frac{1}{\varphi\varkappa_i}\exp(\varphi - y_e)}, \tag{11}$$

where $\varkappa_0 = \varkappa_e + \varkappa_i$, $\varkappa_p = \varkappa_e$,

$$\varphi = -\frac{1}{\varkappa_i} \frac{\exp(-y_e) - (\varkappa_i/\varkappa_e)}{\exp(-y_e) - 1}. \tag{12}$$

Inserting Eq. (11) into (5), with allowance for the expression $q_i^* = \exp(y_e) = \alpha$ we obtain

$$\Psi = \frac{1 - \exp(-y_e)}{1 - \left(\frac{1}{\varphi\varkappa_i} + 1 \right)\exp(-y_e) + \frac{1}{\varphi\varkappa_i}\exp(\varphi - y_e)}, \tag{13}$$

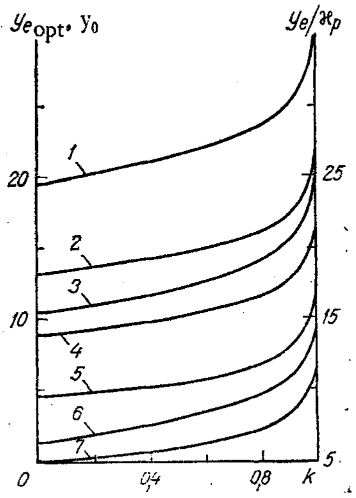

Fig. 2

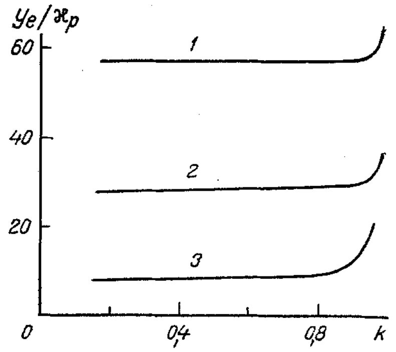

Fig. 3

Fig. 2. Diagram to select optimum parameters of the unit for the scheme in Fig. 1a: 1) $y_e/\varkappa_p = f_1(k)$, 2) $y_e = \varphi_1(k)$, 3) $y_e/\varkappa_p = f_2(k)$, 4) $y_e = \varphi(k)$, 5) $y_e/\varkappa_p = f_3(k)$, 6) $y_e = \varphi_3(k)$, 7) $y_0 = f_4(K)$; 1, 2) $q_e = 1000$; 3, 4, 7) 100; 5, 6) 10.

Fig. 3. Dependence of $y_e/\varkappa_p$ on k at $y_e = y_{eopt}$. 1) $q_e = 1000$, $y_{eopt} = 7.5$, 2) $q_e = 100$, $y_{eopt} = 5$, 3) $q_e = 10$, $y_{eopt} = 3$.

substitution of which into Eq. (10) gives

$$\frac{1}{q_e} = \exp(\varphi)\,\Psi(1-\exp(-y_e)) + \exp(-y_e). \tag{14}$$

With allowance for (5) and (12), we obtain the following from (14)

$$\frac{y_e}{\varkappa_p} = y_e\frac{\alpha-1}{\alpha-(k^*\theta/1-k^*\theta)}\ln\left(q_e\frac{\alpha-1}{\alpha-q_e}\,\frac{1-\theta}{1-\theta k^*}\right). \tag{15}$$

Calculations performed with Eq. (15) showed that there exists a parameter y_{eopt}, dependent on q_e, at which the value of $y_e/\varkappa_p$ is minimal (Fig. 3). However, comparison of the corresponding values of $y_e/\varkappa_p$ in Figs. 2 and 3 shows that the reflux scheme is less efficient for separation.

More interesting results were obtained from a comparison of the schemes in Figs. 1a and 1b. The expression for calculating the surface per unit of product obtained per unit of time is as follows in the case of the scheme in Fig. 1b [8]

$$\frac{y_e}{\varkappa_p} = y_e\frac{1-\theta k^*}{\theta k^*}\,\frac{1}{1+(\theta k^*/1-\alpha)}\ln\left(q_e\frac{1-\theta}{1-\theta k^*}\right) \tag{16}$$

(see Fig. 4). For comparison, the figure also shows similar data for a scheme with entry of the feed in the middle part of the column. This data was obtained from the simultaneous solution of Eqs. (6) and (9) with different values of y_e and q_e. Analysis shows that these schemes are nearly equivalent under optimum conditions at values of $k < 0.5$. At $k > 0.5$, the scheme in Fig. 1a requires less surface per unit of product removed per unit of time. However, such regimes are realized for the scheme in Fig. 1a at higher values of y_e, which presumes the use of serially-connected columns. In this case, there may be a substantial increase in the volume of fluid in the unit due to the presence of connecting pipes and, accordingly, there may be a substantial increase in the duration of transient processes. Thus, the completed analysis shows that the schemes depicted in Fig. 1a, and b are characterized by similar values of $y_e/\varkappa_p$ under optimum conditions. Consequently, the volume and reliability of the lines connecting different columns and the compactness of the equipment layout will be the main factors which determine the preferability of one scheme over another.

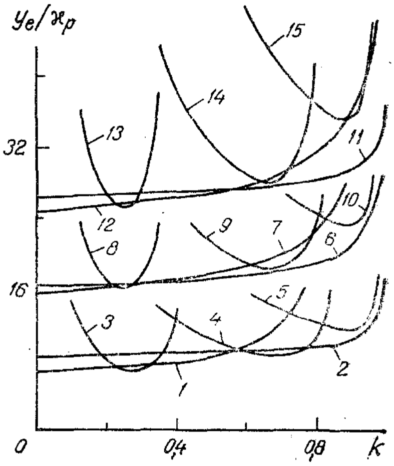

Fig. 4. Dependence of $y_e/\varkappa_p$ on k for the scheme in Fig. 1a at $q_e = 10$: 1) $y_e = 6$; 2) 8; at $q_e = 100$: 6) $y_e = 11$; 7) 8.5; at $q_e = 1000$: 11) $y_e = 12.5$; 12) 18; for the scheme in Fig. 1b at $q_e = 10$: 3) $y_e = 0.5$; 4) 2; 5) 4; at $q_e = 100$: 6) $y_e = 0.5$; 9) 2; 10) 4; at $q_e = 1000$: 13) $y_e = 0.5$; 14) 2; 15) 4.

NOTATION

B, column parameter; c, concentration; D, diffusion coefficient; $H = \alpha_T \rho^2 g \beta \delta^3 (\Delta T)^2 B/6! \eta \bar{T}$; $K = g^2 \rho^3 \beta^2 \delta^7 (\Delta T)^2 B/9! \eta^2 D$; L, column height; y, dimensionless vertical coordinate; α_T, thermodiffusion constant; β, coefficient of thermal expansion; δ, gap in the column; $\varkappa = \sigma/H$, dimensionless rate of removal of product; η, viscosity; σ, rate of product removal. Indices: e, positive end of column; i, negative end; 0, entry point.

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