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Abstract

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ON THE ROLE OF LONGITUDINAL MIXING IN EXCHANGE COLUMNS FOR ISOTOPE SEPARATION

The equation for the concentration gradient of one of the two components in an exchange column for the stationary state is usually written in the form ([1,2]):

$$H\frac{dC}{dz} = \varepsilon C(1-C) - \frac{i(C_k - C)}{I}, \tag{1}$$

where C is the mole fraction of the component being separated in the binary mixture, ε is the enrichment coefficient, C_k is the concentration in the withdrawal, I is the material flow in one of the phases, i is the withdrawal flow, and H is the height equivalent to a theoretical plate (HETP).

The HETP is a function of the flow I and depends on the design and diameter of the column, the type and dimensions of the packing, and does not depend on the concentration C. The task of column theory is to determine the quantity H as a function of I and to predict H for various designs and dimensions of the column and packing.

The construction of such a theory is a difficult problem, and for practical purposes empirical formulas of limited significance are usually used. The purpose of the present note is to establish the influence of longitudinal mixing of the phases on the value of H.

In the following exposition we assume that equation (1) and all the assumptions on the basis of which it was obtained are valid. In particular, in the equilibrium state the distribution of isotopes between phases I and II is determined by the relation:

$$\beta_1 = \alpha\beta_2, \tag{2}$$

where β_1 and β_2 are the isotope ratios, respectively, in phases I and II

$$\left(\beta = \frac{c}{1-c}\right),$$

α is the separation coefficient; $\alpha = 1 + \varepsilon,\ \varepsilon \ll 1$.

For the concentration difference, neglecting ε^2, from (2) we have

$$C_1 - C_2 = \varepsilon\overline{C}(1-\overline{C}), \tag{3}$$

where $\overline{C}$ is any value lying between C_1 and C_2.

The rate of isotope exchange per unit length of the column is determined by the formula:

$$J = I_0[\varepsilon\overline{C}(1-\overline{C}) - (C_1 - C_2)], \tag{4}$$

where J is the flow of the light component from phase II into phase I, and I_0 is the exchange flow.

In the stationary state the flow of the light component along the column is determined by the relation:

$$i_l = IC_1 - (I-i)C_2 - D_1\frac{dC_1}{dz} - D_2\frac{dC_2}{dz}, \tag{5}$$

where terms 3 and 4 of the right-hand side differ from zero when $\frac{dC}{dz} \neq 0$ and determine the flux of the light component caused by longitudinal mixing in the phases.

The change in the flux of the light component with phase I per unit length of the column is equal to the flux of the light component from phase II into phase I; according to formula (4):

$$\frac{d}{dz}\left(IC_1 - D_1\frac{dC_1}{dz}\right) = I_0[\varepsilon\overline{C}(1-\overline{C}) - (C_1 - C_2)]. \tag{6}$$

In columns operating in practice, the quantity $(C_1 - C_2) \ll \varepsilon\overline{C}(1-\overline{C})$. At the same time, the concentration difference over the entire length of the column $(C_k - C_0)$ may be of the order of unity. It follows from this that, with a sufficient degree of accuracy, the relation

$$\frac{dC_1}{dz} = \frac{dC_2}{dz} = \frac{d\overline{C}}{dz}. \tag{7}$$

is satisfied. Then in equation (5) the last two terms of the right-hand side may be replaced by one: $D\frac{d\overline{C}}{dz}$, where $D = D_1 + D_2$ is the coefficient of longitudinal mixing, taking into account the effect in both phases and serving as a process parameter.

For the further derivation of the column equation, in the left-hand side of (6) we neglect the term containing the second derivative with respect to C, as is usually done. Then, solving (5) for the difference $C_1 - C_2$ and substituting the result into equation (6), we obtain:

$$\left(\frac{I}{I_0} + \frac{D}{I}\right)\frac{d\overline{C}}{dz} = \varepsilon\overline{C}(1-\overline{C}) - \frac{i \; - i\overline{C}}{I}. \tag{8}$$

In the transformation carried out, the quantity C_2 was replaced by $\overline{C}$, which can be done with the adopted accuracy, since $\frac{i}{I} \simeq \varepsilon$.

Calculation of $\frac{d^2C}{dz^2}$ from (8) shows the validity, with the adopted accuracy, of neglecting the term containing $\frac{d^2C}{dz^2}$ in (6).

Consideration of (8) gives the value of the HETP in the form

$$H = \frac{I}{I_0} + \frac{D}{I}. \tag{9}$$

When longitudinal mixing is small and $\frac{D}{I} \ll \frac{I}{I_0}$, the HETP is equal to $\frac{I}{I_0}$—the ratio of the flux in the phases to the magnitude of the exchange flux per unit length of the column. The magnitude of the exchange flux I_0 is determined by the dispersity of the phases (the magnitude of the phase-contact surface) and by the kinetics of exchange (chemical or diffusional).

For the experimenter, and especially for the designer, it is important to determine separately the contributions to the HETP caused by the rate of mass exchange and by longitudinal mixing. The usual methods of experimental study of columns, both in the steady-state regime and in the establishment regime, do not make it possible to do this. In all these experiments the only result is the value H, i.e. only the sum

$$\frac{I}{I_0} + \frac{D}{I}.$$

A more refined experiment can be set up to establish the influence of longitudinal mixing. In particular, in the nonselection regime, for $i = 0$, equation (5) becomes (10):

$$D_1\frac{dC_1}{dz} + D_2\frac{dC_2}{dz} = I(C_1 - C_2). \tag{10}$$

By measuring $(C_1 - C_2)$ and $\frac{dC_1}{dz}$, $\frac{dC_2}{dz}$ at two points of the column, we can obtain two equations for determining the mixing coefficients D_1 and D_2. This method, and other similar methods, are very difficult to realize because of the high requirements imposed on the accuracy of isotope analysis. In our opinion, a practically feasible method for the experimental determination of the coefficients D_1 and D_2 is as follows.

A well-defined impurity is introduced into each of the phases as it enters the column. It is necessary that this impurity practically not pass into the other phase. Then, by determining the distribution of the impurity along the length of the column at different moments of time, or the distribution of the impurity with time at the outlet of the given phase from the column, one can determine D_1 and D_2 separately.

The solution of the diffusion equation, under the assumption that the initial distribution of the impurity is concentrated in a sufficiently small segment of length, has the form [3]:

$$C(z,t) = \frac{Q}{2a\sqrt{\pi t}} e^{-\frac{(z-v\,t)^2}{4a^2 t}}, \tag{11}$$

where z is the coordinate along the length of the column, t is time, Q is the amount of impurity introduced, v is the linear velocity of the phase, and $a^2 = D$.

Introducing the impurity at the inlet of the phase into the column and measuring the impurity concentration at the other end of the column, at $z = L$, at different moments of time, we obtain the curve $C(L,t)$, determined by formula (11). Using this curve and formula (11), one can determine the value of the longitudinal mixing coefficient D. In particular, for the time

$$T = \frac{L}{v},$$

we obtain, for calculating D, the simple formula:

$$D = \frac{1}{4\pi} \cdot \frac{Q^2}{C^2(L,T)\frac{L}{v}}. \tag{12}$$

Let us note that in this same experiment, by recording the moment of the maximum concentration at the point L, determined by formula (13),

$$T_{\max} = \frac{L}{v}\left[\sqrt{1 + \left(\frac{a^2}{v\,L}\right)^2} - \frac{a^2}{v\,L}\right], \tag{13}$$

and using formula (11), one can simultaneously determine both D and v.

Thus, the analysis carried out of the column equation and the proposed methods for determining longitudinal mixing make it possible to determine the true value of mass exchange per unit length of the column and the contribution to the HETP caused by longitudinal mixing.

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Note: Figure translations are in progress. See original paper for figures.

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