KINETICS OF DISTILLATION WITH VAPOR (GAS) IN A LAYER

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Based on an analysis of the solution of the differential equation of diffusion and experimental data on the kinetics of distillation, we investigate the problem of the intensity of turbulence in a boundary layer under conditions of bubbling of vapor through a layer of liquid (vegetable oil).

Vapor and liquid differ substantially in density; when vapor bubbles float to the surface, viscosity forces induce circulation in them, and this violates the molecular mechanism of mass transfer.

According to Kronig and Brink [1], there are some volumes of irregular shape in the interior of a sphere (droplet, bubble) (we shall call them Stokes zones) with a common center at the point whose complex coordiante is $\xi = 1$. At all the points of the surface of each Stokes zone the concentration remains unchanged; it changes in going from one zone to another. Circulation decays in the direction toward the center of the internal irregular volumes, i.e., the effective diffusion coefficient is a function of the coordinate. On the surface and near the vapor (gas) bubble the circulation is most intense, since this is the region of "instantaneous" mass transfer through the boundary layer with developed convectivity. Convection within the vapor bubble was confirmed experimentally [2], and in [3] a numerical solution of the problem with a constant D is presented.

Using Kronig and Brink's equation and the graphical dependences of the parameters of the differential equation of mass transfer from [1], we can easily obtain

$$\frac{\partial}{\partial \xi} \left[D_{\text{eff}} (\xi) \frac{\partial c}{\partial \xi} \right] = q (\xi) \frac{\partial c}{\partial \tau} , \tag{1}$$

$$D_{\text{eff}} (\xi) = \frac{16D}{R^2} d (1 - \xi) , \quad \xi = 4r^2 (1 - r^2) \sin \theta .$$

The boundary condition of the third kind, corresponding to the physical picture described, will be written in the form

$$- \frac{\partial c (R , \tau)}{\partial r} + H [c (h , \tau) - c (R , \tau)] = 0 . \tag{2}$$

In accordance with investigations [4], we will adopt the exponential relations

$$c (h , \tau) = c_0 (1 - \exp (- \beta \tau)) , \tag{3}$$

$$c (R , \tau) = c_0 (1 - \alpha \exp (- \beta \tau)) . \tag{4}$$

Taking into account Eqs. (3) and (4), we can write boundary condition (2) in the form

$$- \frac{\partial c (R , \tau)}{\partial r} + Hc_0 (\alpha - 1) \exp (- \beta \tau) = 0 . \tag{5}$$

The concentration difference coefficient, which depends on the degree of turbulence in the boundary layer, varies within the limits $1 \geq \alpha \geq 0$. When $\alpha = 1 - \partial c(R, \tau)/\partial r \to 0$, i.e., when substance transfer through the bubble surface is very intense (the transfer occurs at a small concentration gradient), the boundary condition takes the usual form. The remaining conditions are generally known:

$$c(r, 0) = 0, \quad \partial c(0, \tau)/\partial r = 0, \quad c(0, \tau) \neq \infty.$$

In accordance with [5], the new variable is

$$z = \int_0^\xi \frac{d\xi}{D(\xi)} = -\frac{R^2}{16Dd} \ln(1 - \xi). \tag{6}$$

In Eq. (1)

$$q(z) = z^s. \tag{7}$$

To satisfy the dimensionality condition we must take $s = -1$. Then from [5] we obtain

$$c(z, \tau) = \frac{z}{\Gamma(1)} \int_0^\tau \varphi(\tau) \frac{\exp\left(-\dfrac{z}{\tau - b}\right)}{(\tau - b)^2} d\chi, \tag{8}$$

where $\chi = \tau - b$, and b is the retardation time.

From Eq. (8) we can easily obtain

$$c(z, \tau) = \frac{z \exp(-z/b)}{\Gamma(1) b^2} \int_0^\tau \varphi(\tau) d\tau, \tag{9}$$

where the quantity

$$\varphi(\tau) = c_{p0}(\alpha - 1) \exp(-\beta\tau) \tag{10}$$

is a function on the bubble surface in the vapor phase.

The solution of the problem posed has the form

$$\frac{c(\xi, \tau)}{c_{p0}} = \frac{\dfrac{R^2}{16Dd} \ln(\xi - 1)(\alpha - 1) \exp\left(-\dfrac{R^2 \ln(\xi - 1)}{16Ddb}\right)}{b^2\beta} \times (1 - \exp(-\beta\tau)). \tag{11}$$

Obviously, when $\tau \to \infty$, $c(\xi, \tau)/c_{p0} \to 1$ and Eq. (11) yields

$$\beta = \frac{\dfrac{R^2}{16Dd} \ln(\xi - 1)(\alpha - 1)}{b^2} \exp\left(-\frac{R^2 \ln(\xi - 1)}{16Ddb}\right). \tag{12}$$

The final solution of the problem, after averaging over r and θ, has the simple form

$$\frac{\bar{c}(\tau)}{c_{p0}} = 1 - \exp\left(-\beta\frac{h}{u}\right), \tag{13}$$

where the approximate value of β is

$$\beta \cong \frac{\pi}{2} [0.13 - 7.6 \cdot 10^{-4} \text{Fo}_b^{-1} (2.31 \cdot 10^{-2} - 2.7 \cdot 10^{-4} \text{Fo}_b^{-1})] \times \text{Fo}_b^{-1} (1 - \alpha)/b. \tag{14}$$

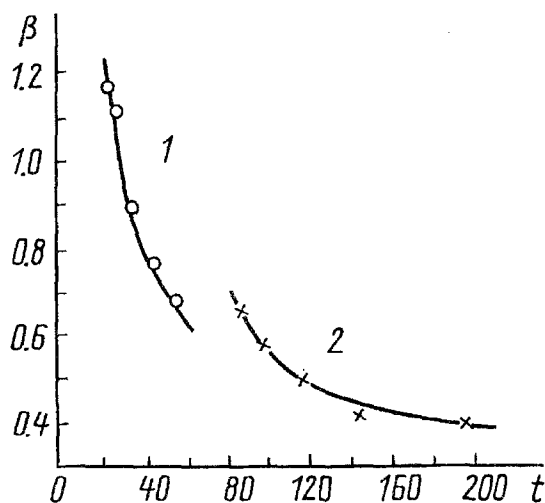In the problem considered, the retardation time b is the time of formation of the vapor bubble. It is obvious that

Fig. 1. The coefficient β as a function in the driving off of extraction gasoline from vegetable oil in a CO_2 current: 1) $h = 25$ mm; 2) 50 mm; $T_{oil} = 373.2$ K, $T_{CO_2} = 473.2$ K, $P = 1.01325 \cdot 10^2$ Pa, $R_0 = 3$ mm, $n = 1$. β, sec^{-1}; t, sec.

$$b = \frac{4\pi R^3 \rho}{3G} .$$
(15)

It should be clarified that the form of formula (14) was determined using the graphs for d from [1]. It is logical to assume that $\beta^{-1} = \tau_n$, and then the entire exponent in Eq. (13) $\beta h/u = \tau/\tau_n$ will physically mean the ratio of the total time of bubbling to the modified time of rise of the vapor bubble.

Having determined u from the formula suggested in [6], we obtain the value of β using experimental data and Eq. (13) (see Fig. 1). In the characteristic cases of distillation studied, the law of the change in β with the time of the process is exponential. Using well-known methods for calculating D and R [6], we determined α from formula (14). In all the cases investigated, α is very close to 1, which corresponds to the adopted concept of intense turbulence in the boundary layer.

NOTATION

c, concentration; c_0, initial concentration of liquid on the basis of the substance driven off; c_{p0}, concentration of substance in vapor in equilibrium with c_0; D, coefficient of molecular diffusion; $D_{eff}(\xi)$, effective diffusion coefficient, which depends on the coordinate; R, bubble radius; r, current radius; d, coefficient; H, mass transfer coefficient; h, height of the liquid layer; u, bubble rise velocity; b, time of bubble formation; $q(\xi)$, some given function of ξ; $\Gamma(1)$, gamma function; t, time of the process; G, vapor (gas) flow rate; α, coefficient of the concentration difference over the boundary layer thickness; β, coefficient of the kinetic equation of driving off; ξ, complex coordinate; τ, time of bubble rise; τ_n, modified time of bubble rise; $Fo_b = Db/R^2$, Fourier number for bubble formation; ρ, density of the vapor (gas).

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