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MASS TRANSFER WITH GAS DESORPTION FROM THE SURFACE OF A LIQUID FILM IN THE PRESENCE OF A COCURRENT FLOW

V. I. Terekhov, V. P. Lebedev, and N. E. Shishkin

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Results of a theoretical and experimental study of dynamics and mass transfer during desorption of a gas from a liquid film in the presence of a cocurrent air flow are presented. The calculation model is based on solving integral momentum and diffusion relations for the gaseous and liquid phases. Both laminar and turbulent regimes of the film flow are analyzed. The experimental study of mass transfer was conducted for carbon dioxide desorption from a water film. Criterial relations for mass transfer in the gaseous and liquid phases are obtained. The experiments showed that the heat-transfer coefficients for the case under study are one order of magnitude greater than those for the flow of a smooth film. Possible mechanisms of such an appreciable intensification of the liquid-film mass transfer in a cocurrent gas flow are discussed.

Generation of a cocurrent gas or vapor flow (or a counterflow) along the gas–liquid interface is an effective method of mass-transfer intensification during gas absorption or desorption in liquid films. This problem was experimentally studied in [1–4] for the case of a gravitational film flow both for ascending and descending motion of the phases. According to the data obtained, the influence of a cocurrent flow on mass transfer is rather complex. For instance, for gas velocities $V_0 < 5$ m/sec, the cocurrent flow exerts practically no effect on mass transfer, and the mass-transfer rate depends only on the film Reynolds number Re_s. For vapor velocities $V_0 > 10$ m/sec, the mass-transfer rate in the film increases sharply, and for $\mathrm{Re}_s = \mathrm{const}$, a linear dependence of the mass-transfer coefficient on the gas-flow velocity is observed. This phenomenon is observed both for a cocurrent flow and counterflow of a gas or vapor, and at $V_0 = 40$–50 m/sec the mass-transfer rate increases almost by a factor of ten compared to a purely gravitational descending flow of the film with an identical Reynolds number.

An increase in the film Reynolds number leads to a more pronounced effect of the cocurrent flow on the mass transfer between the phases. In experiments of Nikolaev et al. [3], it was found that the mean rate of mass transfer increases with decreasing length of the surface along which the liquid film flows down. In this case, the dynamic and diffusional boundary layers become thinner, which intensifies the dynamic interaction between the phases leading to an enhanced convective mass transfer in the gaseous and especially in the liquid phases.

More detailed numerical simulations [4–6] and experimental results [3, 4, 7] showed that the sharp increase in the heat- and mass-transfer rate is caused predominantly by a more intense agitation of the liquid over the film thickness due to origination of waves of various amplitudes and frequencies on the free surface of the film. Formation of drops and secondary interaction between the drops captured by the flow and the liquid surface also exert a certain effect on the process. According to [8], under conditions of a drop flow, the mass-transfer coefficients can be three or four times higher than the coefficients for a film flow.

The problem of mass transfer between a liquid film and a cocurrent gas flow is a multi-parametric

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Kutateladze Institute of Thermal Physics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 41, No. 4, pp. 131–138, July–August, 2000. Original article submitted June 16, 1999.

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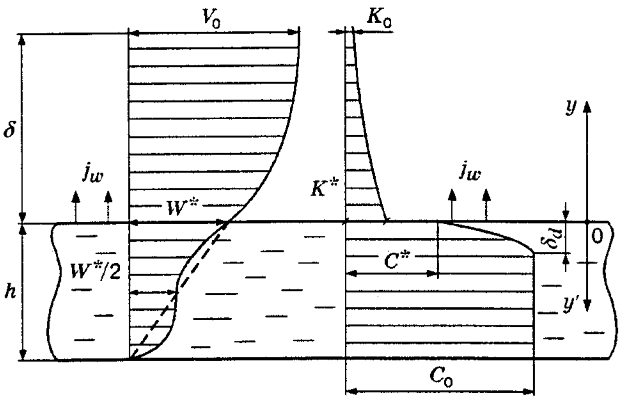

Fig. 1

one; therefore, to calculate the mass-transfer rate under such conditions, one can use simple models based on solving integral relations for momenta and diffusion in a gas or liquid. In the present work, in this statement of the problem, we consider the dynamics and mass transfer during desorption of a poorly soluble gas from a liquid film for laminar and turbulent regimes of the gas flow. Results of an experimental study of desorption of carbon dioxide dissolved in water into a cocurrent air flow are described. The main objective was to determine regularities of mass-transfer variation along the film, and also the mass-transfer coefficients and integral parameters for both the gaseous and liquid phases.

1. Model of Interphase Interaction between a Film and a Cocurrent Gas Flow. The scheme of the flow under study is shown in Fig. 1. A liquid film with a gas dissolved in it is supplied along an infinite flat surface and is set into motion by a gas flow through shear stresses. Conditions of equality of velocities and shear stresses are fulfilled at the interface. We consider a stabilized section of the film flow. Here, the velocity profile under conditions of a laminar flow is linear; under conditions of a turbulent flow, it is a self-similar one and consists of two boundary layers merging together, one at the interface between the phases and the other on the rigid wall [9]. The film Reynolds number $\mathrm{Re}_s = q/\nu_{\mathrm{liq}}$ is assumed to be constant over the length because the crossflow of the desorbed gas is weak. Here $q = \bar{W}h = W_sS$ is the volume flow rate of the liquid through a unit width of the flow, $\bar{W} = (1/h)\int\limits_0^h W\,dy'$ is the mass-mean velocity of the film, W_s is the velocity of the film in the initial section, S is the inlet width of the slot through which the liquid is supplied, and h is the current film thickness. The velocity W^* at the interface between the phases and the film thickness h depends on the longitudinal coordinate.

The thickness of the diffusional boundary layer is small compared to the film thickness ($\delta_d \ll h$) due to the low diffusivity of poorly soluble gases in water. Natural conditions at the interface between the phases are the continuity of the crossflow of the substance j_w and the interrelation of mass concentrations of the desorbed component in the liquid and gaseous phases described by Henry's law:

$$C^* = \Gamma_k K^*, \tag{1}$$

where C^* and K^* are the mass concentrations of the desorbed gas at the interface in the liquid and gaseous phases and Γ_k is Henry's coefficient ($\Gamma_k = 590$ for carbon dioxide dissolved in water under normal conditions [10]).

The integral equations of momenta and diffusion for the boundary layer in the gas phase are [11]

$$\frac{d\,\mathrm{Re}^{**}}{d\bar{x}} = \frac{C_f}{2}(1 - b_1)\,\mathrm{Re}_L; \tag{2}$$

$$\frac{d\,\mathrm{Re}_d^{**}}{d\bar{x}} + \frac{\mathrm{Re}^{**}}{\Delta K}\,\frac{d(\Delta K)}{d\bar{x}} = \mathrm{St}_d(1 - b_{1d})\,\mathrm{Re}_L. \tag{3}$$

Here $\mathrm{Re}^{**} = \delta^{**}\Delta V_0/\nu_{\mathrm{gas}}$, $\mathrm{Re}_d^{**} = \delta_d^{**}\Delta V_0/\nu_{\mathrm{gas}}$, and $\mathrm{Re}_L = L\Delta V_0/\nu_{\mathrm{gas}}$ are the Reynolds numbers based on the momentum and mass thickness and on the length, respectively, $C_f/2$ is the friction coefficient at the interface between the phases. $b_1 = 2j_w/(\rho_0\Delta V_0 C_f)$ and $b_{1d} = j_w/(\rho_0\Delta V_0\,\mathrm{St}_d)$ are the dynamic and diffusional permeability parameters, respectively, $\mathrm{St}_d = -\rho D(dK/dy)^*/(\rho_0\Delta V_0\Delta K)$ is the mass-transfer coefficient, $\Delta V_0 = V_0 - W^*$ is the relative velocity, $\Delta K = K^* - K_0$ is the concentrational head, and $\bar{x} = x/L$ is the dimensionless longitudinal coordinate.

The integral equations for the liquid phase have a form similar to (2) and (3).

The conditions at the interface can be written in the form

$$V_{\mathrm{gas}} = W_{\mathrm{liq}} = W^*, \qquad \tau_{\mathrm{gas}}^* = \tau_{\mathrm{liq}}^* = \tau_w, \qquad j_{\mathrm{gas}}^* = j_{\mathrm{liq}}^*. \tag{4}$$

Using the equation of conservation of mass at the wall, we can rewrite the last relation of (4) as

$$\rho_{\mathrm{liq}} D_{\mathrm{liq}}\left(\frac{\partial C}{\partial y'}\right)^* \frac{1}{1 - C^*} = -\rho_0 D_{\mathrm{gas}}\left(\frac{\partial K}{\partial y}\right)^* \frac{1}{1 - K^*}. \tag{5}$$

The coordinates y and y' are directed from the gas–liquid interface into the gaseous and liquid phases, respectively (Fig. 1).

Since the conditions $C^* \ll 1$ and $K^* \ll 1$ are fulfilled during gas absorption and desorption, expression (5) can be simplified to

$$K^* = \frac{C_0 - C^*}{1/\Gamma + (\mathrm{St}_{d,\mathrm{gas}}/\mathrm{St}_{d,\mathrm{liq}})2\rho_0\Delta V_0/(\rho_{\mathrm{liq}}W^*)} - K_0. \tag{6}$$

The estimates show that $C_0 \gg C^*$; hence, during desorption of poorly soluble gases ($\Gamma \gg 1$) into an inert flow ($K_0 \to 0$), relation (6) acquires the form

$$K^* = C_0\frac{\mathrm{St}_{d,\mathrm{liq}}\rho_{\mathrm{liq}}W^*}{2\,\mathrm{St}_{d,\mathrm{gas}}\rho_0\Delta V_0}. \tag{7}$$

The concentration of the desorbed gas K^* depends on the concentration of this gas dissolved in the liquid C_0, on the ratio of mass-transfer coefficients in the liquid and gaseous phases, and also on the mass velocities of the film and air flow.

Relations (1)-(7) are valid both for laminar and turbulent flows of the gas and liquid phase. The flow conditions determine the values of the friction coefficient $C_f/2$ and the heat-transfer coefficient St_d which enter Eqs. (2) and (3) and also similar relations for the liquid phase.

The turbulent regime of the cocurrent gas flow is of greatest interest for practical applications. In this situation, the film flow may be either laminar or turbulent. Below, we will study these regimes separately.

Turbulent-Laminar Regime. An analysis of experimental data on absorption and desorption of gases from films [1-5, 7] showed that the crossflow of substance at the interface is weak; hence, its influence on the laws of friction and mass transfer may be ignored. Consequently, the permeability parameters are close to zero ($b_1 = b_{1d} \approx 0$), and the friction and mass-transfer coefficients are $C_f/C_{f0} = \mathrm{St}_d/\mathrm{St}_{d0} \approx 1$, where $C_{f0}/2$ and St_{d0} are the friction amd mass-transfer coefficients under conditions without a crossflow of substance on the surface. Hence, Eqs. (2) and (3) transform into equations that describe friction and mass transfer in a standard boundary layer [11]. Then the relations for calculating friction and mass transfer can be written in the following form:

— in the gaseous phase,

$$\tau_{\mathrm{gas}}^* = 0.029\rho_0\Delta V_0^2\,\mathrm{Re}_x^{-0.2}, \qquad \mathrm{St}_d = 0.0362\,\mathrm{Re}_x^{-0.2}\,\mathrm{Sc}_{\mathrm{gas}}^{-0.6}; \tag{8}$$

— in the liquid phase with allowance for the linear velocity profile,

$$\tau_{\mathrm{liq}}^* = -\left(\mu_{\mathrm{liq}}\frac{dW}{dy'}\right)^* = \mu_{\mathrm{liq}}\frac{W^*}{h}, \qquad \mathrm{St}_{d,\mathrm{liq}} = 0.332\,\mathrm{Re}_{x,\mathrm{liq}}^{-1}\,\mathrm{Sc}_{\mathrm{liq}}^{-2/3}. \tag{9}$$

Here $\mathrm{Re}_x = \Delta V_0 x/\nu_{\mathrm{gas}}$ and $\mathrm{Re}_{x,\mathrm{liq}} = W^*x/\nu_{\mathrm{liq}}$ are the Reynolds numbers based on the longitudinal coordinate for the gaseous and liquid phases, respectively, and $\mathrm{Sc}_{\mathrm{gas}} = \nu_{\mathrm{gas}}/D_{\mathrm{gas}}$ and $\mathrm{Sc}_{\mathrm{liq}} = \nu_{\mathrm{liq}}/D_{\mathrm{liq}}$ are the Schmidt numbers for carbon-dioxide diffusion in air and water, respectively.

The self-similar velocity and concentration profiles in the gaseous and liquid phases have the form

$$\frac{\Delta V}{\Delta V_0} = \frac{K - K^*}{K_0 - K^*} = \left(\frac{y}{\delta}\right)^n, \qquad 0 < y < \delta; \tag{10}$$

$$\frac{C - C^*}{C_0 - C^*} = 2\frac{y'}{\delta_d} - \left(\frac{y'}{\delta_d}\right)^2, \qquad 0 < y' < \delta_d. \tag{11}$$

The volume flow rate of the liquid per unit width of the film is given by the relation $q = \int_0^h W\,dy' = \frac{W^*h}{2} = W_sS$.

Provided that the cocurrent gas flow is a developed turbulent one ($n = 1/7$), from relations (8)–(10) under the assumption that $W^* \ll V_0$, we obtain the equation for the velocity at the interface

$$\frac{W^*}{V_0} = 0.24\left(\frac{\rho_0}{\rho_{\text{liq}}}\right)^{1/2} \text{Re}_s^{1/2}\text{Re}_x^{-0.1}. \tag{12}$$

Accordingly, the expression for the film thickness is

$$\frac{h}{x} = 8.3\left(\frac{\rho_{\text{liq}}\nu_{\text{liq}}^2}{\rho_{\text{gas}}\nu_0^2}\right)^{1/2} \text{Re}_s^{1/2}\text{Re}_x^{-0.9}. \tag{13}$$

Solving the diffusional problem, we obtain the following expression for the mass flux of the desorbed gas on the film surface:

$$\frac{j_w}{\rho_0 V_0} = 0.115\left(\frac{\rho_{\text{liq}}}{\rho_0}\right)^{3/4} \left(\frac{\nu_{\text{liq}}}{\nu_{\text{gas}}}\right)^{1/2} \text{Re}_s^{1/4}\text{Re}_x^{-0.55} b_{1,\text{liq}}\,\text{Sc}_{\text{liq}}^{-2/3}. \tag{14}$$

Here $b_{1,\text{liq}} = (C_0 - C^*)/(1 - C^*)$ is the diffusional permeability parameter determined for the liquid phase.

Turbulent-Turbulent Regime. Expressions for the velocity, film thickness and mass-transfer coefficients can be derived in a manner similar to the previous case of the turbulent-laminar regime if the laws of friction and mass transfer and also the velocity and concentration profiles for a turbulent film are used instead of relations (9) and (11). As a result, the formulas for the velocity at the interface, the film thickness, and the flux of the desorbed gas across the interface acquire the form

$$W^*/V_0 = 2.08(\rho_0/\rho_{\text{liq}})^{1/2}\text{Re}_s^{1/8}\text{Re}_x^{-0.1}, \quad h/x = 0.961(\rho_{\text{liq}}\nu_{\text{liq}}^2/(\rho_0\nu_{\text{gas}}^2))^{1/2}\text{Re}_s^{7/8}\text{Re}_x^{-0.9},$$
$$j_w/(\rho_{\text{gas}}V_0) = 0.0325(\rho_{\text{liq}}/\rho_0)^{0.6}(\nu_{\text{liq}}/\nu_{\text{gas}})^{0.2}\text{Re}_s^{0.1}\text{Re}_x^{-0.28} b_{1,\text{liq}}\,\text{Sc}_{\text{liq}}^{-0.6}. \tag{15}$$

It follows from relations (12)–(15) that the local characteristics of the film in the cocurrent flow depend on the Reynolds numbers Re_s and Re_x. In addition, the velocity at the interface depends on the ratio of gas and liquid densities, and the film thickness and the crossflow of substance depend on the ratio of their viscosities.

The effect of the Reynolds numbers Re_s and Re_x on the ratio of velocities W^*/W_s and the film thickness h is illustrated in Fig. 2. Curves 1 and 2 show the data for the turbulent–laminar and turbulent–turbulent interactions. The velocity at the interface between the phases (Fig. 2a) was calculated for the ratio of the velocities of the film and inlet cocurrent air flows $W_s/V_0 = 0.05$. The behavior of the parameters W and h is seen to be appreciably different for the two flow regimes. Moreover, as follows from Fig. 2a, varying the ratio of the film and air-flow Reynolds numbers, one can either decrease or increase the velocity at the interface compared to the initial film velocity W_s. The regime parameters also exert a similar effect on the film thickness.

Figure 2b shows the calculated and experimental [12] mean film thickness vs. Re_s for the case with a cocurrent gas flow. Good agreement between the theoretical and experimental data can be noted. The slight discrepancy observed may be attributed to the fact that, according to the data of [12], the behavior of the film thickness and its wavelike variation depend on the flow regime and injection ratio $m = \rho_{\text{liq}}W_s/(\rho_0V_0)$.

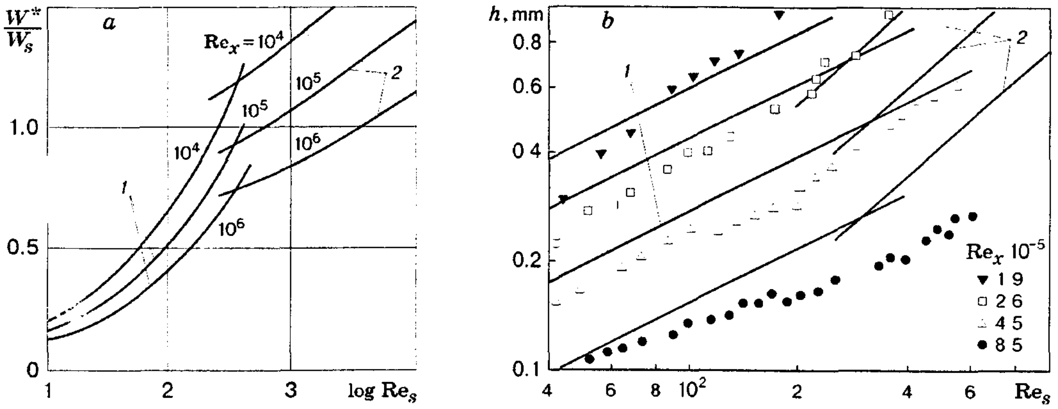

Fig. 2

2. Experimental Study of Mass Transfer from the Film Surface in a Cocurrent Flow. The tests were conducted on a setup described in detail in [8]. The test channel was the initial section of a tube of diameter $D_0 = 0.1$ m and length $L = 0.5$ m. Distilled water saturated with carbon dioxide was fed to the inlet through a tangential slot of height $S = 0.5$ mm. The film Reynolds number was $\mathrm{Re}_s = 100$–150. The velocity of the cocurrent air flow was $V_0 = 25$–45 m/sec, which provided for a uniform thickness of the film along the channel generatrix. According to the charts of regimes of two-phase interaction [13, 14], a flow with three-dimensional waves on the surface corresponds to these conditions; for velocities $V_0 > 30$ m/sec, entrainment of drops can exert a strong effect on the flow. The Reynolds number of the air flow $\mathrm{Re}_0 = V_0 D_0/\nu_0$ ensured a turbulent flow regime ($\mathrm{Re}_0 > 10^5$), and the injection parameter in the tests was $m = 5$–10. Variation of the concentration of the desorbed gas along the film was measured by sampling the substance with a subsequent titrimetric analysis. The flux of the substance across the interface measured in the tests is given by the expression

$$j_w = q\Delta C/\Delta x,$$

where $\Delta C = C_{\mathrm{in}} - C_x$ is the difference between the values of the $\mathrm{CO_2}$ concentration averaged over the cross-sectional area of the film at the channel inlet and in the current cross section; the values of the crossflow averaged over the current coordinate were determined in the experiments. The concentration of the dissolved gas at the outer boundary of the diffusional layer was determined from the mean value of carbon-dioxide concentration measured in the section under consideration and from the calculated thickness of the diffusional boundary layer according to the procedure described in [15].

Variation of mass concentrations of the gas dissolved in the film and of the crossflow of substance at the interface is shown in Fig. 3a. The greatest changes in the concentration and, hence, in the mass flux are observed at the initial section of the film. The experimental values of the relative mass flux (Fig. 3b) obtained for various flow conditions show a tendency toward generalization. Simultaneously, the flux of the desorbed gas is small [$j_w/(\rho_0 V_0) \sim 10^{-5}$]; hence, its influence on the laws of friction and mass transfer may be ignored. Curves 1 and 2 in Fig. 3b show the calculated fluxes of substance across the interface between the phases for the turbulent-laminar and turbulent-turbulent flow regimes, respectively. The calculations were carried out for the experimental mean inlet concentration of the dissolved gas $C_{\mathrm{in}} = 8.5 \cdot 10^{-1}$. For convenience of comparison, the calculated and experimental values of $j_w/(\rho_0 V_0)$ are shown in different scales (left and right scales, respectively). The notation of the points here is the same as in Fig. 3a.

It follows from Fig. 3b that the difference between the experimental and calculated values for the turbulent–turbulent regime is about one order of magnitude, and for the turbulent-laminar flow this difference is even greater.

At the next stage, we performed a criterial treatment of the experimental results. The mass-transfer coefficients were determined for the liquid and gaseous phases individually:

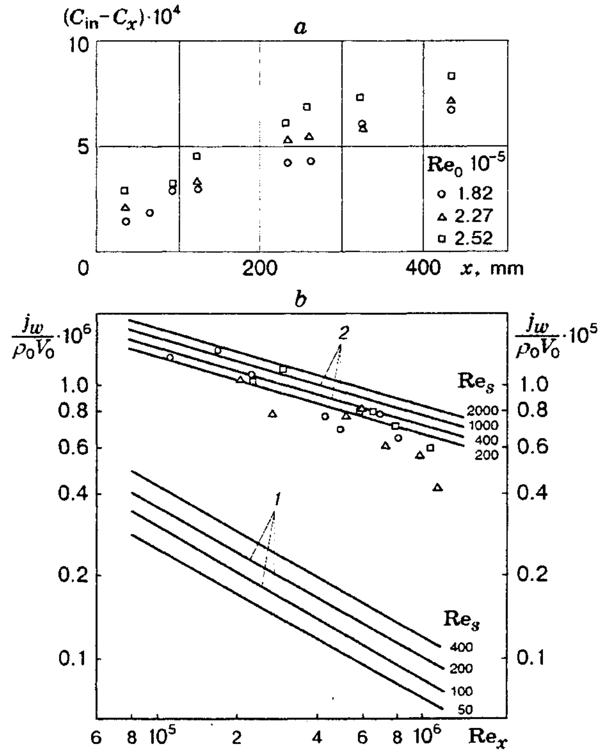

Fig. 3

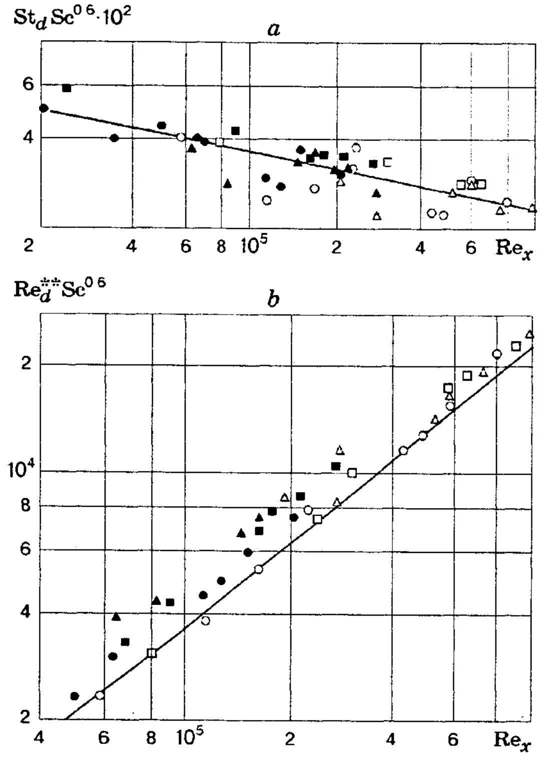

Fig. 4

$$\mathrm{St_{liq}} = 2j_w/(\rho_{\mathrm{liq}}W^*b_{1,\mathrm{liq}}), \qquad \mathrm{St_{gas}} = j_w/(\rho_0V_0b_{1,\mathrm{gas}}).$$

Here $b_{1,\mathrm{liq}} = (C_0 - C^*)/(1 - C^*)$ and $b_{1,\mathrm{gas}} = (K^* - K_0)/(1 - K^*)$ are the permeability parameters. Under the assumption adopted above, we have $b_{1,\mathrm{liq}} \approx C_0$ and $b_{1,\mathrm{gas}} \approx K^*$.

The experimental value of the mass thickness was also determined for each phase separately. From the integral diffusional relation (3) for the gaseous phase, it follows that

$$\mathrm{Re}_d^{**} = \frac{1}{\mu_0 K^*}\int_0^x j_w\,dx.$$

The diffusion equation for the gas dissolved in the liquid has a similar form.

The experimental data on the diffusional Stanton numbers for the gas and liquid boundary layers (open and filled points, respectively) are shown in Fig. 4a. The notation of the points here corresponds to the regime parameters in Fig. 3. In spite of the considerable scatter of experimental data, it can be concluded that they correspond to a turbulent flow regime characterized by the correlation dependence

$$\mathrm{St}_d = 0.36\,\mathrm{Re}_x^{-0.2}\mathrm{Sc}^{-0.6}. \tag{16}$$

The turbulent character of mass transfer is more clearly confirmed by the data in Fig. 4b, which shows the experimental dependence of the Reynolds number based on the mass thickness on Re_x. This dependence is described by the empirical formula

$$\mathrm{Re}^{**} = 0.41\,\mathrm{Re}_x^{0.8}\,\mathrm{Sc}^{0.6}. \tag{17}$$

Here the power exponent at the Reynolds number Re_x corresponds to the turbulent law of mass transfer ($n = 0.8$).

It should be noted that, despite the considerable difference of the diffusivities of CO_2 in liquid and air (Sc = 670 and 0.93, respectively), the experimental points in Fig. 4 for the mass transfer in the film and air boundary layer are described by a universal dependence due to the continuity of the mass flux of the desorbed gas at the interface between the phases. The difference in diffusional resistances in the gaseous and liquid phases is determined by Schmidt numbers.

A comparison of the experimental correlations (16) and (17) with the laws of heat and mass transfer in a turbulent boundary layer on a smooth impermeable wall [11] shows that the rate of mass transfer from the film surface is an order of magnitude greater than under standard conditions. This is confirmed by numerical and experimental data shown in Fig. 3b. Such an intense mass transfer is primarily caused by the wavy character of the film flow, and the mass transfer in a film flowing downward cocurrently with a gas flow is more intense than in a gravitational turbulent film [7]. The enhanced mass transfer may be caused by emulsification of liquid films observed experimentally [16] and by entrainment of drops from the film surface [1, 3–5, 12, 13], which, however, requires further studies.

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