MASS TRANSFER FROM A SINGLE GAS SLUG

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UDC 66.071.5:532.59

The process of mass transfer from a single gas slug to the liquid is investigated experimentally and theoretically. The mass transfer and hydrodynamics of flow over a slug are represented visually.

Few publications have been devoted to questions of mass exchange in the slug mode of flow of gas–liquid mixtures. In [1-3] the mass-transfer coefficients were measured only for single short slugs in laminar flow, and it was found that the mass-transfer coefficient decreases with an increase in slug length. Of interest among theoretical investigations is [1], in which the mass-transfer coefficient for slightly soluble gases was calculated under the assumption that the liquid flow velocity is the same along each normal to the surface.

Experimental Apparatus and Procedure

The coefficients of mass exchange between the phases were measured on the apparatus shown in Fig. 1. The working liquid is supplied from the lower-level tank 1 by the pump 2 to the upper-level tank 3 and then flows down through the measurement section 5 into the lower-level tank. Shutoff–regulating valves 6 are placed before the inlet to the measurement section and after it. The measurement sections consist of glass tubes with a length of 0.5 m and an inside diameter of 6.1, 6.7, 7.4, 8.6, 9.3, 11.8, 12.5, 14.5, and 19 mm. A branch pipe was fused to the lower part of the measurement section for supplying gas from the tank 8. The length of the slug was determined from the scale 4. The instant of reading the slug length was recorded by the timer 7. The measurements were made as follows: A certain portion of carbon dioxide gas was supplied to the measurement section through the side branch and then a liquid flow rate was established with the regulating valves 6 such that the slug remained stationary. This slug was photographed with the camera 9 simultaneously with the scale and the timer three to four times at intervals of 5 sec. To calculate the mass-transfer coefficient we wrote the balance equation

$$\frac{dV}{dt} = -\beta S, \tag{1}$$

$$V = \pi (a - \delta_0)^2 (l - a + \delta_0) + \frac{2}{3} \pi (a - \delta_0)^3, \tag{2}$$

$$S = 2\pi (a - \delta_0)(l - a + \delta_0) + 3\pi (a - \delta_0)^2 \tag{3}$$

under the assumption that the nose of the slug has the shape of a hemisphere, the tail part is flat, and the thickness of the liquid film between the slug and the tube wall is constant. Substituting (3) and (2) into (1), we find

$$(a - \delta_0)^2 \frac{dl}{dt} = -\beta_2 [2(a - \delta_0)(l - a + \delta_0) + 3(a - \delta_0)^2]. \tag{4}$$

Integrating (4), we obtain the equation

$$\beta = \frac{a - \delta_0}{2(t_2 - t_1)} \ln \frac{2l_1 + a - \delta_0}{2l_2 + a - \delta_0},$$

where l_1 and l_2 are the lengths of the slug at times t_1 and t_2.

All the measurements were made for a system of carbon dioxide and distilled water. The temperature of the liquid was monitored and comprised 20°C ± 0°.5. The accuracy in measuring

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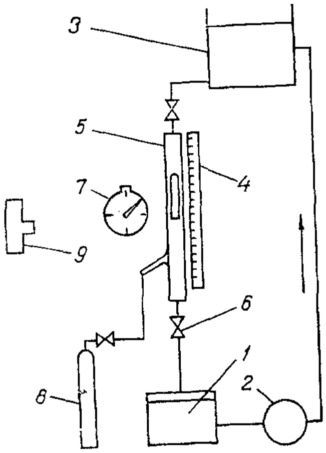
Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 48, No. 4, pp. 533-538, April, 1985. Original article submitted April 25, 1984.



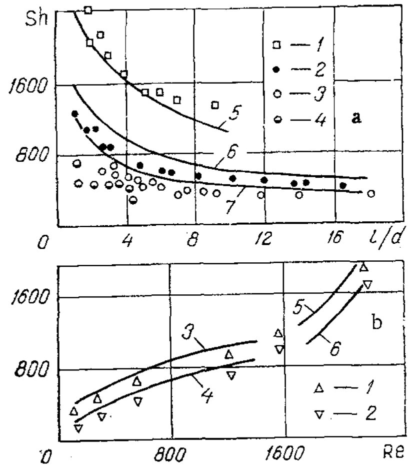


Fig. 1 Fig. 2

Fig. 1. Diagram of the experimental apparatus.

Fig. 2. Dependence of Sh on l/d and on Re: a) experiments on tubes of diameters of: 1) 1.92 cm; 2) 0.93; 3) 0.67; 4) 0.48 [1]; calculation from Eqs.: 5) (21) and (23); 6, 7) (12) and (16); b) experiments on slugs with lengths of: 1) 4 cm; 2) 8; calculation from Eqs.: 3, 4) (17); 5, 6) (24).

the length of a slug was ±0.5 mm and the accuracy in measuring the time corresponding to a given length was ±0.01 sec. The results of the determination of the mass-transfer coefficients are presented in Fig. 2. The change in the character of the dependence of Sh on Re in the transition to turbulent liquid flow is clearly seen in Fig. 2b.

Visual Representation of the Mass-Transfer Process

In the case of a continuous chain of slugs, the question of the concentration profile ahead of the nose of a slug arises. To estimate the limits of the Reynolds numbers for which the wake behind a slug remains unblurred, we made a visual representation of the mass transfer from a gas slug floating up in a liquid. A portion of a mixture of ammonia and air was supplied to the water-filled tube. Phenolphthalein, colorless in plain water, was added to the water. The ammonia gave an alkaline reaction upon dissolving and colored the phenolphthalein red. The completely unblurred wake behind a slug for Re = 60 is well seen in Fig. 3a. With and increase in Re to 70 (Fig. 3b) the stability of the wake is disrupted and the concentration profile in the wake behind the slug becomes impulsive.

Calculation of the Mass-Transfer Coefficient

The calculation was made under the following assumptions: The velocities of liquid motion in the concentration boundary layer and along the phase interface are equal; the mass-exchange processes do not alter the hydrodynamics of flow over the slug; the radius of curvature of the slug is much greater than the thickness of the diffusional boundary layer.

We assume that the liquid flow velocity along the interface is given by the relation $V_z = cz^n$. The transverse velocity component is found from the continuity equation. Then the diffusion equation with two convective terms is written as

$$V_z \frac{\partial c}{\partial z} + V_r \frac{\partial c}{\partial r} = D \frac{\partial^2 c}{\partial r^2} \tag{5}$$

with the boundary conditions

$$r = 0 \quad c = c_s, \tag{6}$$

$$r \to \infty \quad c = c_\infty, \tag{7}$$

where the z axis is directed along the phase interface while the r axis is perpendicular to it.

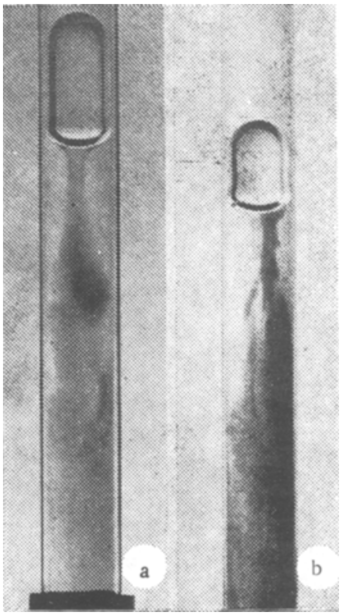


Fig. 3. Visual representation of the mass-transfer process: a) Re = 60; b) 70.

Introducing the self-similar variables $\eta = r\left[\frac{D}{c(n+1)}\right]^{1/2} z^{\frac{n-1}{2}}$, we find the solution of (5):

$$c = c_1 \int_0^{\eta} \exp\left(-\frac{1}{4}\eta^2\right) d\eta + c_2. \tag{8}$$

Using (6) and (7), we obtain an expression for the concentration distribution of the gas dissolved in the liquid:

$$c = \frac{c_\infty - c_s}{\sqrt{\pi}} \int_0^{\eta} \exp\left(-\frac{1}{4}\eta^2\right) d\eta + c_s. \tag{9}$$

Substituting (9) into the equation $q = -D\left.\frac{\partial c}{dr}\right|_{r=0}$ and considering that descending flow exists at the nose of the slug [4] while the liquid velocity is constant in the film, we obtain the equations for calculating the mass-transfer coefficient at the nose of the slug:

$$\beta = \frac{\sqrt{D}}{\sqrt{\pi}} (4.5)^{1/4} g^{1/4} z^{-1/4}, \tag{10}$$

$$\bar{\beta} = \frac{\sqrt{D}}{\sqrt{\pi}} \frac{4}{3} (4.5)^{1/4} g^{1/4} l^{-1/4}, \tag{11}$$

$$\mathrm{Sh} = 1.3\,\mathrm{Pr}^{1/2} \nu^{-1/2} g^{1/4} d^{3/4} \left(\frac{l}{d}\right)^{-1/4}, \tag{12}$$

$$\mathrm{Sh} = 2.57\,\mathrm{Pr}^{1/2} g^{-1/2} \nu^{1/3} l^{-1/4}\,\mathrm{Re}^{2/3}. \tag{13}$$

In the liquid film

$$\beta = \sqrt{\frac{DV_0}{\pi z}}, \tag{14}$$

$$\bar{\beta} = \sqrt{\frac{DV_0}{\pi l}}, \tag{15}$$

$$\overline{\mathrm{Sh}} = 0.41\,\mathrm{Pr}^{1/2} \nu^{-2/3} g^{1/3} d \left(\frac{l}{d}\right)^{-1/2}, \tag{16}$$

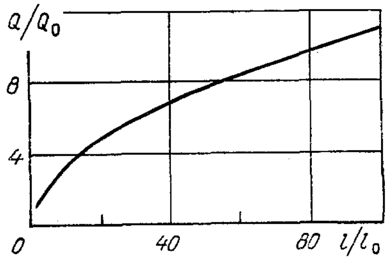


Fig. 4. Dependence of Q/Q_0 on l/l_0.

$$\overline{\mathrm{Sh}} = 0.59\,\mathrm{Pr}^{1/2}\,\nu^{-1/3}\,g^{1/6}\,l^{-1/2}\,\mathrm{Re}^{1/3}, \tag{17}$$

$$V_0 = \frac{g\delta_0^2}{3\nu}, \tag{18}$$

$$\delta_0 = \frac{0.9\nu^{1/3}\,a^{1/2}}{g^{1/6}}. \tag{19}$$

To calculate the mass-transfer coefficient for the turbulent mode of flow over a slug we take the turbulent diffusion coefficient in the form [5]

$$D_0 = \chi L V,$$

where L is the characteristic size, V is the average velocity, and χ is a constant, since for the head of the slug [6]

$$L = \delta = 0.17a^{3/2}\,z^{-1/2},$$

while

$$V = \sqrt{2gz},$$

$$D_0 = \chi 0.17\,\sqrt{2g}\,a^{3/2}.$$

Writing the diffusion equation with boundary conditions analogous to (5)-(7) and solving it, we obtain

$$\beta = \frac{4}{3\sqrt{\pi}}\,\chi^{1/2}\,(0.17)^{1/2}\,(2g)^{1/2}\,a^{3/4}\,(1.5)^{1/2}\,l^{-1/4}, \tag{20}$$

$$\mathrm{Sh} = 0.32\,\mathrm{Pr}\,\nu^{-1}g^{1/2}\,\chi^{1/2}\,d^{1/2}\left(\frac{l}{d}\right)^{-1/4} \tag{21}$$

$$\mathrm{Sh} = 1.08\,\mathrm{Pr}\,\nu^{1/6}\,g^{-1/12}\,l^{-1/4}\,\mathrm{Re}^{7/6}. \tag{22}$$

In the liquid film $D_0 = \chi\delta_0 V_0$, where δ_0 and V_0 are determined from Eqs. (18) and (19), so that

$$\overline{\mathrm{Sh}} = 0.12\chi^{1/2}\,\mathrm{Pr}\mathrm{Ar}^{7/12}\left(\frac{l}{d}\right)^{-1/2}\bar{\rho}^{-7/12}, \tag{23}$$

$$\overline{\mathrm{Sh}} = 0.59\chi^{1/2}\,\mathrm{Pr}\,\mathrm{Re}^{3/2}\,\mathrm{Ar}^{-1/6}\,\bar{\rho}^{1/6}, \tag{24}$$

with $\bar{\rho} = (\rho_1 - \rho_2)/\rho_1 \approx 1$.

Comparing the results of calculations from (21) and (23) with experiment, we find that $\chi = 2.58 \cdot 10^{-6}$.

Using the approach of [7, 8], we find that the length of the head of a slug, where the law $V_z = \sqrt{2gz}$ is satisfied, is

$$l_0 = 4.3 \cdot 10^{-2}\,a^2 g^{1/3}\,\nu^{-2/3}, \tag{25}$$

while the length of the transitional zone is small, so that in calculating the mass-transfer coefficients one can neglect its influence and determine the mass-transfer coefficient at the nose of the slug from Eqs. (12) and (13) and that in the liquid film from Eqs. (16) and (17). In Fig. 2a a calculation from Eqs. (12), (16), (21), and (23) is compared with experiment. Points 4 are the results of tests [1] on short slugs in a tube with an inside diameter of 0.48 cm. Some discrepancy between the theoretical curves and experimental points in Fig. 2a is explained by the fact that the use of the equations $V_z = \sqrt{2gz}$ and (18) yields a somewhat overstated value of the mass-transfer coefficient because the influence of surface-tension forces has a retarding action on the nose of the slug, while in the liquid film the diffusional boundary layer can have a significant thickness. In Fig. 2b the calculated curves display agreement with experiment to within 15%. Equations (3), (15), (11), and (13) allow one to determine the contribution of the head to the total mass flux from the slug. It is seen from Fig. 4 that for a slug floating up in a tube with an inside diameter of 0.67 cm the contribution of the liquid film equals the contribution from the head when the length of the slug is five times greater than the length of the head for long slugs.

Thus, it was shown experimentally that a laminar mode of flow over a slug exists for Re < 70; the mass-transfer coefficient decreases with an increase in the slug length. The contribution of the base of the slug to the mass transfer does not alter the character of the dependence of the mass-transfer coefficient on the slug length and on Re.

NOTATION

D, molecular diffusion coefficient; D_0, turbulent diffusion coefficient; δ, thickness of liquid film; δ_0, asymptotic thickness of liquid film; r, z, coordinates; V_r, V_z, velocity components; ω, buoyancy velocity of slug; β, mass-transfer coefficient; Sh, Sherwood number; Re, Reynolds number; Pr, Prandtl number; d, tube diameter; a, tube radius; ν, viscosity of liquid; l, slug length; c, concentration of gas dissolved in the liquid; c_s, saturation concentration; Q_0, mass flux from the head of the slug; Ar, Archimedes number; ρ_2, gas density; ρ_1, liquid density.

LITERATURE CITED

1. J. W. Van Heuven and J. W. Beek, "Gas absorption in narrow gas lifts," Chem. Eng. Sci., 18, No. 3, 377-390 (1963).
2. W. E. Agnew and A. R. Becker, "The rate of solution of nitrogen and oxygen by water. Part I," Philos. Mag., 38, No. 4, 317-324 (1919).
3. W. E. Agnew and A. R. Becker, "The rate of solution of nitrogen and oxygen by water. Part II," Philos. Mag., 39, No. 6, 385-404 (1920).
4. G. B. Wallis, One-Dimensional Two-Phase Flow, McGraw-Hill, New York (1969).
5. G. N. Abramovich, Theory of Turbulent Jets [in Russian], Gos. Izd. Fiz.-Mat. Lit., Moscow (1960).
6. G. K. Batchelor, An Introduction to Fluid Dynamics, Cambridge University Press (1967).
7. L. I. Sen', V. I. Voronov, N. G. Il'yashenko, and V. V. Efimov, Computer Calculation of SEU Parameters [in Russian], Izd. Dal'nevost. Politekh. Inst., Vladivostok (1976).
8. S. S. Kutateladze and V. E. Nakoryakov, Heat and Mass Exchange and Waves in Gas–Liquid Systems [in Russian], Nauka, Novosibirsk (1984).