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MASS TRANSFER FROM A WALL TO A GAS-LIQUID FLOW IN AN INCLINED FLAT CHANNEL

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Experimental study is made of mass transfer from a wall to a gas-liquid flow in an inclined flat channel. Measurements are made by the electrodiffusional method. It is shown that maximum values of mass transfer correspond to intermediate ones of inclination angles of the channel. The effect of the gas phase structure on mass transfer is examined.

Use of multiphase flows is one of the means to enhance heat and mass transfer between a solid body and a liquid. Among them, arranging a two-phase gas-liquid flow is most convenient and simply implemented in practice. In a number of processes, e.g., under electrodeposit of metals, the gas-liquid flow can be initiated due to natural gas liberation in the course of a chemical reaction on a solid surface. Beyond that point, the gas-liquid flow can be artificially initiated by admitting a gas into a liquid. As is well known, the two-phase flow structure is not uniquely defined by the value of liquid and gas flowrates and depends on many other parameters [1]. In particular, of importance are the geometrical dimensions of the channel and its orientation relative to the vertical. A variety of flow regimes of a gas-liquid flow makes it impossible to theoretically predict flow and mass transfer coefficients, as this generates a need for experimental studies of such processes.

Mass transfer in a gas-liquid flow was investigated in a number of works. Works [2, 3] were concerned with free convective mass transfer due to the relative motion of a gas phase with no liquid flowrate. The effect of the geometry of a channel and its orientation was examined. In [2], it was shown that under free convection the maximum mass transfer intensity corresponded to the horizontal channel position. Mass transfer from a gas and a liquid simultaneously flowing in a vertical channel was analyzed in [4]. It was found that at a constant gas flowrate mass transfer decreased with increasing reduced liquid velocity.

From the presented brief review it follows that the literature lacks reported data on mass transfer from a liquid and a gas moving simultaneously in an inclined flat channel. The importance of studying the effect of the channel orientation on the process intensity is associated with the fact that the channel position essentially affects the gas-liquid flow structure because of the buoyancy force. Moreover, the inclined channel is the simplest model of an element of curvilinear channels frequently encountered in different commercial devices.

The work is aimed at investigating mass transfer from a two-phase gas-liquid mixture flowing in a flat channel as its orientation changes. Mass transfer between a solid surface and a flow was measured.

The experimental setup is illustrated schematically in Fig. 1. A liquid was supplied by centrifugal pump 1 via a system of rotameters 2 to working section 3, at whose inlet the gas-liquid flow was arranged. A two-phase mixture entered into top tank-separator 4 from the working section outlet. Then the liquid was drained into bottom tank 5, from which it was again supplied to the pump. To provide constant physical properties the working liquid was thermostatted by means of heat exchanger 6 mounted in the bottom tank. Cooling water supply to the heat exchanger was controlled by an automatic thermostatting system. The tank liquid temperature was measured by a semiconductor thermometer, whose output signal controlled the thermostatting system.

The high-pressure line air passed through reducer 7, filter 8, and regulating valve 10, whereupon it was supplied to mixer 11. The air flowrate was measured by rotameter 9. The working section was a flat rectangular 10 × 100 mm channel. The channel inlet was equipped with a prechamber 40 × 100 mm in cross section. The prechamber

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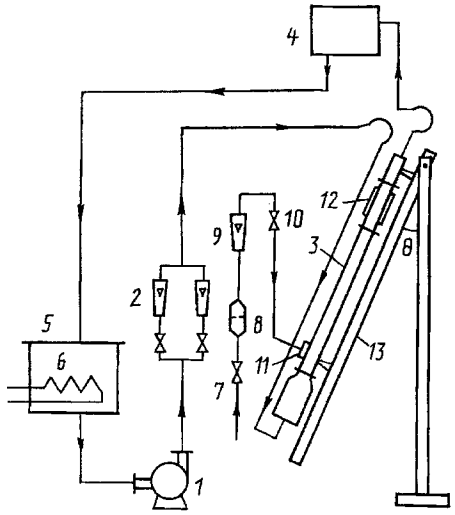


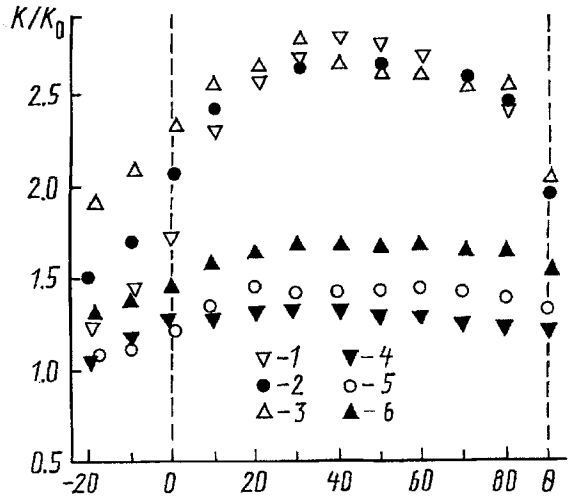


Fig. 1. Schematic of the experimental setup.

Fig. 2. Mass transfer coefficient as a function of channel inclination angle; V_l = 0.36 m/sec: 1) $\beta = 0.05$; 2) 0.1; 3) 0.2; V_l = 1.04 m/sec: 4) $\beta = 0.05$; 5) 0.1; 6) 0.2.Θ, deg.

was mated with the flat channel via a profiled nozzle. Measuring tank 12 was placed in the top part of the working section. The working section was fastened on rotating frame 12, which could rotate around its horizontal axis. The working section was connected with the fastened delivery and drain tubes via flexible silicone rubber pipes.

A solution of 0.005 potassium n-ferri- and ferrocyanide and 0.25 M sodium carbonate in distilled water was used as the working liquid. Mass transfer was measured by the electrodiffusion method [5]. The measuring unit was a flat channel 10 × 100 mm in inner cross section and 440 mm in length. Two windows were cut in the wide walls of the unit to install a cathode and an anode. The windows were placed opposite to each other. The anode was a steel 90 × 260 mm plate glued in flush with the channel wall. The 40 × 180 mm cathode was located symmetrically relative to the channel axis. Eight local 4.8 mm diameter sensors electrically insulated from the large cathode were embedded along the cathode axis. The working cathode and anode surfaces were coated with a 10-μm-thick nickel layer by electrolytic deposition.

The mass transfer coefficient was measured by the standard methods [6]. The anode was grounded, the bias voltage relative to the anode was fed to the cathode, and the diffusion current was then measured. As the magnitude of the diffusion current changed in time due to flow pulsations, the current of the local sensors was measured by a current amplifier and an integrator with an integration time of 10 or 20 sec. The mass transfer coefficient K was determined in terms of the measured current of the sensor I by the formula

$$K = I/(FSC_0),$$

where F is the Faraday number (F = 96,500 C/mole); S is the electrode surface area; C_0 is the ferricyanide ion concentration.

To initiate the gas-liquid flow at the working section inlet a mixer was mounted behind the prechamber. It was a detachable insert placed in the channel wall window. The gas was admitted through 20 holes 0.35 mm in diameter. The start of the measuring cathode was at a distance of 450 mm from the point of gas admission. The mixer and the cathode were mounted on the same wall of the flat channel.

In measurements with a constant liquid flowrate the gas flowrate changed and the diffusion current was measured. Measurements in the two-phase flow were obligatorily preceded by calibrations of the sensors in the single-phase flow. The flowrate gas constant by volume β was determined by the formula $\beta = V_g/(V_l + V_g)$ where V_l, V_g are the reduced liquid and gas velocities; the gas velocity was found at atmospheric pressure.

In the course of the experiments mass transfer vs channel orientation was studied. The angle Θ was reckoned from the vertical (Fig. 1). The value Θ = 0 agreed with the vertical position of the channel, and Θ = 90°, with the

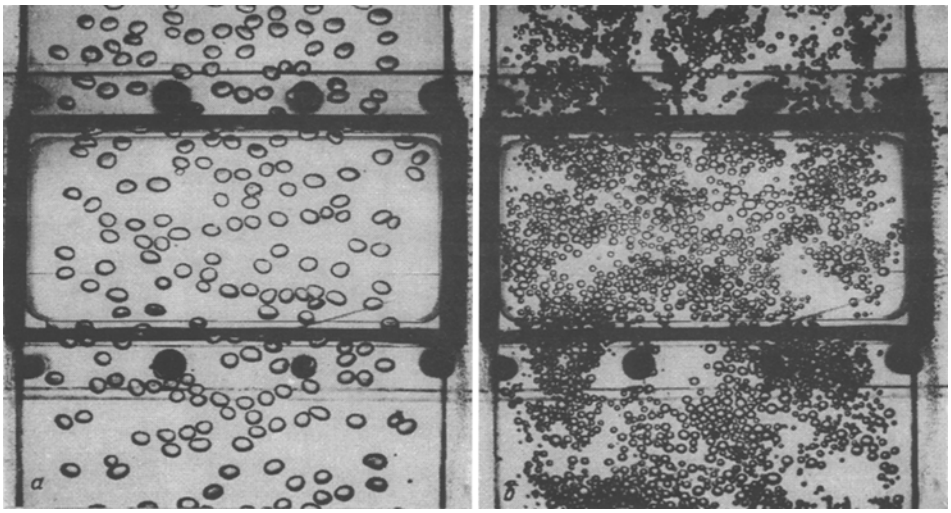


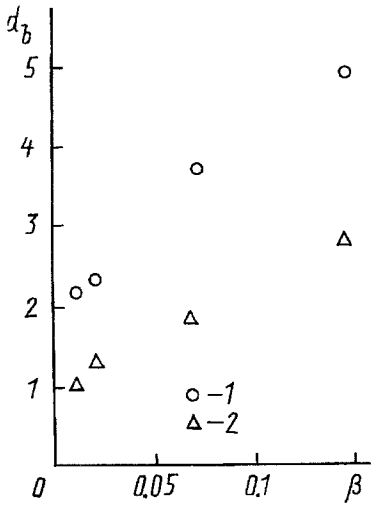
Fig. 3. Flow structure when different mixers are used.

horizontal one. At positive values of the angle Θ the cathode was positioned with its surface downwards. Mainly, just this case was analyzed because for such a cathode position the influence of the gas phase on mass transfer was the greatest.

Results on the measured mass transfer coefficient K in the gas-liquid flow are plotted in Fig. 2 for two values of the reduced liquid velocity V_l at different flowrate gas contents β. Here K_0 is the mass transfer coefficient in the single-phase flow at the same value of the reduced liquid velocity. It is seen that the channel orientation exerts a significant influence on mass transfer. Maximum values of K are attained at intermediate values of the angle Θ = 30-50°. It should be noted that qualitatively, a similar behavior of mass transfer has been observed for all values of V_l. K/K_0 also depends on the flowrate gas content, increasing with its growth. The change of the reduced liquid velocity is opposite: with increasing V_l the values of K/K_0 decrease.

The obtained dependence of the mass transfer on the channel inclination angle may be explained as follows. When Θ changes, the gas phase concentration distribution over the channel cross section changes. At the expense of the buoyancy force effect the bubbles move to the upper channel wall (on which the sensor-cathode is mounted). With increasing inclination angle a profile of the local gas content with a maximum must develop near the upper wall: the position of the maximum must approach the wall as the horizontal channel position is attained. Naturally, the greatest influence on mass transfer must be exerted by bubbles moving near the wall. In what follows, their influence on the flow characteristics must be the greater, the larger the velocity of the bubbles relative to the liquid (buoyancy velocity). A maximum value of the mass transfer coefficient for the inclined channel position is associated with the fact that in this case, the bubbles are "pressed" as much as possible against the upper wall while the buoyancy velocity still remains high. As the horizontal position is reached, the relative bubble velocity decreases, thus diminishing the disturbing action of the bubbles on the flow and, accordingly, reducing the mass transfer. The behavior of the bubbles in the flow, in particular, the degree of their concentration in the wall region, must depend on their size.

Arranging the flow with a fixed size of the gas bubbles is an extremely intricate problem. For the simple-design mixer utilized in the present work the gas bubble size depended both on the liquid velocity and on the gas content. An attempt was made to obtain a gas-liquid mixture with bubbles of substantially smaller size. With this in mind, the working section inlet was provided with a similar-design mixer but with a different size of the gas admission holes. This mixer has 49 holes 0.15 mm in diameter arranged in seven rows spaced at 10-mm intervals. As is known, in the case of free bubble departure from a hole the departed-bubble size is proportional to the cube root of the hole diameter. In our experiment, this dependence is not satisfied since the liquid velocity near the hole is different from zero. Nevertheless, when the second mixer is employed, it is possible to initiate the gas-liquid flow where the bubble size is much smaller than the one in the first case. It is natural that when the second mixer was utilized, the bubble



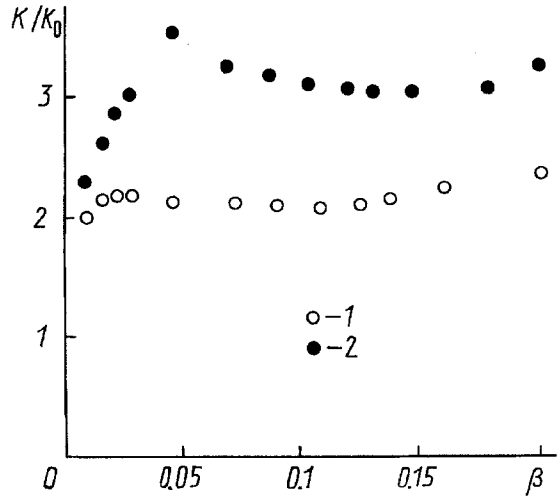


Fig. 4. Mean gas bubble size; $V_l = 0.49$ m/sec: 1) mixer 1; 2) mixer 2. d_b, mm.

Fig. 5. Effect of the mixer type on mass transfer; $V_l = 0.49$ m/sec: 1) mixer 1; 2) mixer 2.

size is much smaller than the one in the first case. It is natural that when the second mixer was utilized, the bubble size also depended to a certain extent on the reduced liquid velocity and the flowrate gas content. Figure 3 shows photographs of the gas-liquid flow when the first and second mixers are used. It is seen that for all flow regimes the size of the bubbles generated by the second mixer is approximately twice smaller compared to the first case. Figure 4 presents the values of the mean bubble diameter for different gas contents at the same reduced liquid velocity. With increasing β the quantity d_b increases. This is apparently concerned with violating the conditions for single separation. Thus, the change in the mass transfer coefficient due to changing flowrate gas content also involves the effect of the change in bubble size.

As measurements of the mass transfer intensity (see Fig. 2) over the range of channel inclination angles from 30 to 50° show, the quantity K practically remains constant. The angle $\Theta = 40^\circ$ is chosen as the characteristic one. The mass transfer coefficient as a function of flowrate gas content at a constant liquid velocity for this inclination angle is depicted in Fig. 5 for both types of mixers. The effect of the gas bubble size on the mass transfer is clearly seen. For small bubbles (mixer 2) the values of K are substantially higher for all gas contents. This result is not obvious and cannot be explained by a simple model. Apparently, of importance is the fact that with decreasing bubble size they start to be disposed closer to the wall and their disturbing effect on the wall region of the flow grows. Some possible decrease in the buoyancy velocity is insignificant. For small bubbles the nonmonotonic behavior of K vs β is of interest. A sharply pronounced maximum is seen at $\beta = 0.05$. A similar effect of gas bubble size on wall shear stress in a vertical tube under nucleation conditions is noted in [7].

The presented measurement results show that the hydrodynamic flow structure exerts a determining influence on the mass transfer between the wall and the gas-liquid flow. The local gas content distribution in the wall layer and the relative gas bubble velocity near the wall are the most important factors. Unfortunately, at present these problems cannot be solved theoretically. As a consequence, the hydrodynamics of gas-liquid flow in a channel should be studied in detail in order to analyze the mass transfer process.

It should be noted that initiating the gas-liquid flow with a given-size gas-phase distribution is of fundamental importance to control the mass transfer process. This poses the problem of designing more perfect mixers. Apparently, only at the expense of gas phase dispersion control can the mass transfer process efficiency be substantially increased.

Relying on the performed measurements, the following conclusions can be made:

1) admitting a gas phase into the ascending liquid flow enhances mass transfer in all the channel orientations under study;

2) a maximum value of the mass transfer coefficient is attained at inclination angles of 30 to 50° relative to the vertical;

3) the gas bubble size is the predominant parameter that affects the mass transfer intensity under constant flowrates of the liquid and gas: mass transfer increases with decreasing bubble size.

NOTATION

C_0, active ion concentration, mole/m^3; α_b, mean gas bubble size, mm; F, Faraday number, C/mole; I, sensor current, A; K, mass transfer coefficient, m/sec; K_0, mass transfer coefficient in the single-phase flow, m/sec; S, electrode area, m^2; V_l, V_g, reduced liquid and gas velocities, m/sec; β, flowrate gas content by volume; Θ, channel inclination angle, deg.

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