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MASS TRANSFER IN A JET DEVICE

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The process of mass transfer in a jet device has been investigated by the evaporation of water. Methods of calculating the interface formed by gas bubbles and measuring the mass-transfer coefficient have been developed. The experimental and calculated mass-transfer coefficients have been compared.

Problems on the use of jet devices for initiation of mass-transfer processes were investigated at the Polotsk State University over the course of several years.

To this point, jet devices have been used in the chemical industry mainly as blowers and ejectors [1]. The possibilities of using these devices for other purposes, e.g., in aeration systems or for effecting of a mass transfer between different media, are scantily known. The prospects of using jet devices in chemical engineering stem from their advantages over other analogous devices: the absence of rotating and rubbing parts and their simple design. Jet devices can operate in any flow of a substance (gas, liquid), which allows them to be used for initiation of biotechnological processes and intensification of mass transfer. With jet devices, the interface in a liquid layer can be increased without recourse to special contact devices. The use of jet devices also makes it possible to solve the problem of energy conservation, which is of great practical importance at present.

It is agreed that the main characteristic of a mass-transfer process [2] is the ejection coefficient

$$K_{\mathrm{e}} = \frac{Q_{\mathrm{g}}}{Q_{\mathrm{liq}}} . \tag{1}$$

The Mach number is used as the main criterion at large Reynolds numbers [2]:

$$\mathrm{M} = \frac{w_{\mathrm{liq}}}{W_{\mathrm{s}}} . \tag{2}$$

In the case where a gas is ejected by a jet of a liquid, friction forces arise on the surface of interaction of the liquid with the gas in the process of flow out of the liquid from a nozzle and a turbulence is formed in the liquid flow. In this case, the turbulence of the liquid flowing out from the nozzle (with a velocity of $w_{\mathrm{liq}} \approx 15$ m/sec) is characterized, as in aeromechanics, by the velocity of sound propagating in the liquid medium. This hydrodynamic criterion is described in detail in [3]. It was established experimentally that the quality of this ejection depends on the ratio between the diameters of the nozzle and the mixing chamber. In the case where cylindrical nozzles and air pits are used, the optimum ratio between their diameters is 0.22–0.23. The regularities of the mass transfer in a jet device were experimentally investigated on a laboratory test bed (Fig. 1).

A laboratory jet device comprises a glass cylinder 1 clamped in a metal mandrel. An air pit 2, into which air is ejected by a water flow, is inserted into the cylinder. The pit serves to supply a low-moisture air for initiation of mass-transfer processes in an aerator. The water circulating around a closed path enters nozzle 8. The water pressure is determined by manometer 3. The ejected-air flow rate is measured by rotameter 6. Air enters the jet device through union 4. Continuous circulation of water in the system is provided by a centrifugal pump 5. The mixture of air with water vapor passes through union 7 to the atmosphere. The function of the device, in which a mass-transfer process is initiated, is saturation of air with water vapor.

In experiments, round nozzles of diameter $d_{\mathrm{n}} = 5$ and 8 mm were used. The cone angle of the nozzles was 30° in both cases. In the process of investigations, we measured and calculated the following quantities: φ, saturation

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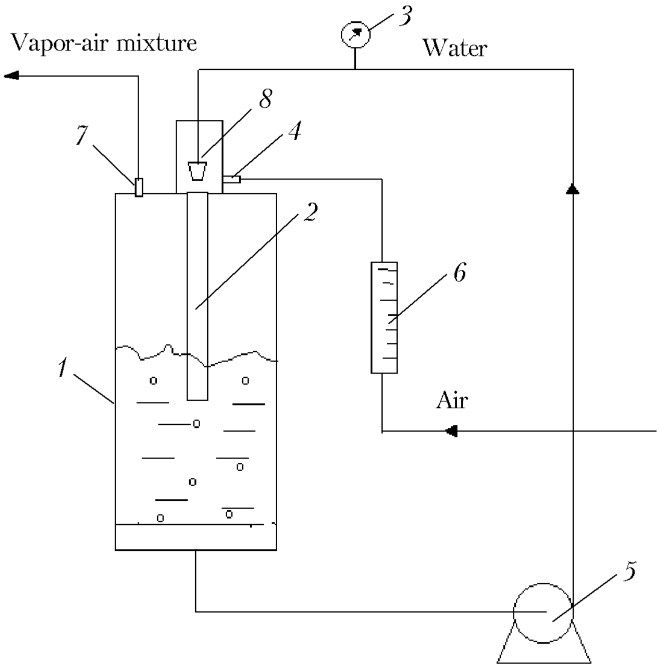

Fig. 1. Laboratory test bed of a jet aerator for mass-transfer processes.

of a layer with gas; N, number of gas bubbles forming a layer; F, interface; amount of moisture evaporated in a unit time. Experiments were carried out at different temperatures of the medium and different levels of submergence of the mixing chamber into the aeration layer for the purpose of determining the complete pattern of formation of the interface (mass-transfer surface) and the mass-transfer kinetics.

In the process of experiments, we made photographs of the aeration of a stationary liquid layer with a vertical gas-liquid jet. On the basis of the statistical data obtained by processing of the photographs made, we determined the average volume-surface diameter of a gas bubble in the aerated layer for different nozzles. Analysis of the photographs has shown that all bubbles have a clearly defined spherical shape and their sizes are practically equal throughout the aeration layer. For d_n = 5 mm, d_b = 3.35 mm, and, for d_n = 8 mm, d_b = 3.42 mm.

The interface F was calculated by the following method. The values of V_g and V_{layer} were determined experimentally. The volume of the gas in the aerated layer was calculated by the formula

$$V_g = \frac{\pi d_d^2}{4} H_g \, . \tag{3}$$

For each liquid-flow rate, an increase in the gas-layer height H_g, as compared to the initial (stationary) level of liquid in the device, was measured using a marked scale plotted on the aerator. The volume of the aerated layer was determined on the basis of the experimental data by the equation

$$V_{\text{layer}} = 0.785 d_d^2 (H_g + H_{\text{layer}}) \, . \tag{4}$$

In the case where the diameter of a gas bubble and its volume are known, the number of bubbles N in the aeration layer can be determined by the formula

$$N = \frac{V_{\text{layer}}}{V_b} \, . \tag{5}$$

Knowing the area of one spherical bubble and the total number of bubbles in the layer, one can determine the interface F formed by gas bubbles:

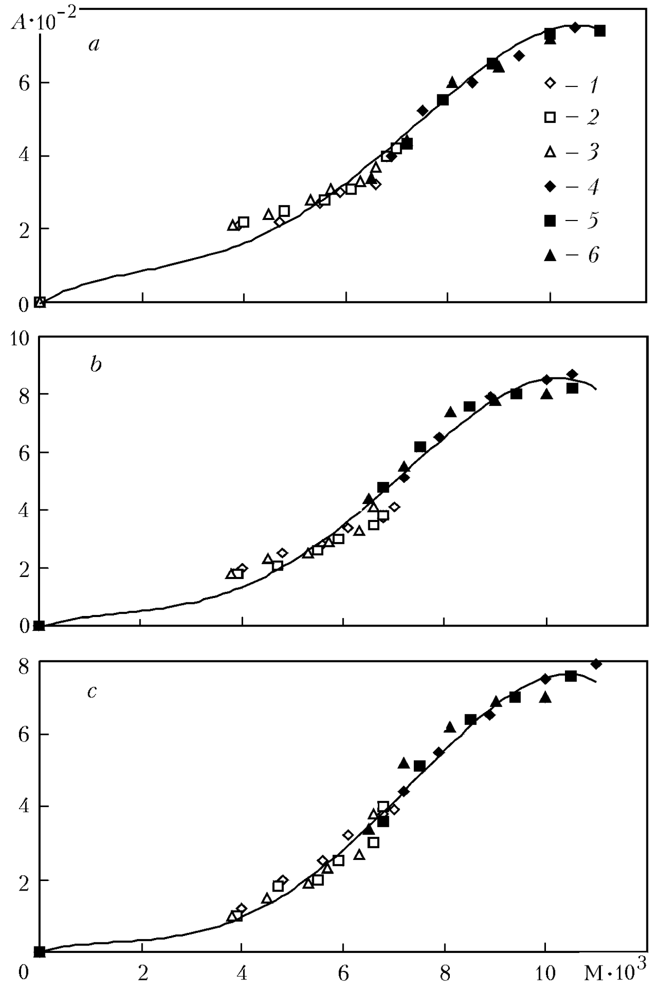

Fig. 2. Dependence of the relative mobile surface of mass transfer on the Mach number for the pits positioned higher than the aeration mirror (a) and at the interface (b) and for the pit immersed in the aeration layer (c): d_n = 8 mm and t = 25 (1), 38 (2), and 48°C (3); d_n = 5 mm and t = 25 (4), 38 (5), and 48°C (6).

$$F = F_b N = \pi d_b^2 N . \tag{6}$$

The experimental data obtained were generalized to the mass-transfer surface with the use of the dependence of the relative mobile interface, defined as $Fw_b/Q_{liq} \equiv A$, on the Mach number. The generalized graphs were constructed for different temperatures and positions of the mixing chamber relative to the aeration mirror and two values of the nozzle diameter: d_n = 5 and 8 mm (Fig. 2). As is seen from the figure, the dependence represents an S-like curve that is widely met in chemical engineering.

The mass transfer was investigated by the evaporation of water from the jet device to an air flow because, in this case, the resistance of the liquid phase can be disregarded and it may be assumed that $\beta_{g,exp} \approx K_g$. The mass-transfer coefficient was calculated by the formula

$$K_g = \beta_{g,exp} = \frac{\Delta V_{w.v}/\Delta\tau}{F\Delta P} P . \tag{7}$$

The motive force of the mass-transfer process is equal to the difference between the equilibrium and operating partial pressures of the water vapor

TABLE 1. Comparison of Mass-Transfer Coefficients

d_n, mm	$\beta_{g,exp,av}$	$\beta_{g,calc}$	$\beta_{g,calc,av}$ (formula (12))
5	3.1	3.7—25	3.8
8	3.7	4.1—31	4.2

$$\Delta P = P^* - P_{op} . \tag{8}$$

The operating pressure is determined from the equation

$$P_{op} = \frac{\frac{\Delta G_{w.v}}{\rho_{w.v}}}{\frac{\Delta G_{air}}{\rho_{air}} + \frac{\Delta G_{w.v}}{\rho_{w.v}}} P = \frac{V_{w.v}}{V_{air} + V_{w.v}} P , \tag{9}$$

where

$$\frac{\Delta G_{w.v}}{\rho_{w.v}} = \frac{\pi R^2 \Delta H \rho_w}{\Delta \tau \rho_{w.v}} . \tag{10}$$

Note that the ratio between the equilibrium and operating pressures is larger than 1.15.

To verify the validity of the experimental data on the mass-transfer coefficients, we compared them with the analogous calculation data obtained by formulas presented in the literature. The mass-transfer coefficient $\beta_{g,calc}$ was determined using the Nusselt diffusion criterion by the formula

$$\beta_{g,calc} = \frac{\mathrm{Nu}_g D_g}{d_b} . \tag{11}$$

Different authors calculated the diffusion coefficients and the Nusselt criterion dependences for the mass-transfer processes arising as a result of the barbotage of a liquid by a gas by different formulas [4–7], for example, by the formula [5]

$$\mathrm{Nu}_g = 0.43 \mathrm{Re}_g^{0.56} \mathrm{Pr}_g^{0.33} , \tag{12}$$

where

$$\mathrm{Re}_g = \frac{w_b d_b \rho_g}{\mu_g} .$$

It was established experimentally that the rate of rise of a gas bubble upward w_b is 0.095 m/sec for d_n = 8 mm and 0.073 m/sec for d_n = 5 mm.

The experimental and calculated data on the mass-transfer coefficient, obtained for the nozzles of two diameters, are compared in Table 1. It is seen from this table that, for the nozzle of diameter d_n = 5 mm, the average value of the theoretical mass-transfer coefficients is 3.8 and the average value of the experimental coefficients is 3.1. For the nozzle with d_n = 8 mm, the corresponding values are 4.2 and 3.7. In this case, the difference between the theoretical and experimental mass-transfer coefficients comprises 18% for the nozzle of diameter 5 mm and 14% for the nozzle of diameter 8 mm. The theoretical values of the mass-transfer coefficients calculated by different formulas are very different. The experimental mass-transfer coefficients agree satisfactorily with the mass-transfer coefficients calculated by formula (12). We compared the experimental data with the corresponding calculation data obtained using this equation.

CONCLUSIONS

1. A developed interface formed by gas bubbles in the process of jet aeration is larger than the surface of an aeration mirror by several orders of magnitude. The interface sharply increases when the Mach number exceeds a critical value (see Fig. 2). Intensive processes of mass transfer occurring in a jet device provide the attainment of a near-equilibrium state.

2. The theoretical coefficients of mass transfer determined by different formulas are very different. The experimental coefficients of mass transfer agree satisfactorily with the mass-transfer coefficients calculated by formula (12). It should be noted that the experimental values of the mass-transfer coefficients are also somewhat different.

3. The mass-transfer processes in the device considered can be calculated using the known generalizations for the mass transfer in a liquid–gas system. The main problem of these calculations is correct determination of the interface formed by gas bubbles depending on the aerohydrodynamics of the jet aeration and, in particular, on the ejection coefficient and the range of a jet in a concrete process of mass transfer.

NOTATION

D_g, gas molecular-diffusion coefficient, m^2/sec; d_d, diameter of a jet device (0.112); d_n, diameter of a nozzle, m; d_b, diameter of an air bubble, m; Fo, Fourier criterion; F_b, area of the bubble surface, m^2; F, interface, m^3; $\Delta G_{w.v}$, amount of evaporated water, kg/sec; ΔG_{air}, amount of ejected air, kg/sec; H_g, height of the gas layer arisen in the process of aeration above the aeration mirror characterizing the gas-layer volume, m; H_{layer}, depth of penetration of a gas bubble into an aerated-liquid layer, m; ΔH, difference between the water levels in the device before and after an experiment measured for a certain time, m; K_g, mass-transfer coefficient related to a unit surface, $m^3/(m^2 \cdot sec)$; K_e, ejection coefficient; M, Mach number; N, number of bubbles in an aerated layer; Nu_g, Nusselt diffusion criterion for gas; ΔP, motive force of the process, atm; P_p, equilibrium partial pressure of the saturated water vapor, atm; P, total pressure of the system (atmospheric), atm; P_{op}, operating partial pressure of the water vapor, atm; Pr, Prandtl number; Q_g, volumetric rate of gas flow, m^3/h; Q_{liq}, volumetric rate of liquid flow, m^3/h; R, radius of the aeration mirror, m; Re_g, Reynolds number for the gas phase; t, temperature of the medium, ^oC; $\Delta V_{w.v}$, volume of the evaporated water, m^3; $V_{w.v}$, rate of water-vapor flow, m^3/h; V_{air}, air flow rate, m^3/h; V_g, volume of the gas in an aerated layer, m^3; V_{layer}, volume of the whole aerated layer, m^3; V_b, volume of a spherical gas bubble, m^3; w_{liq}, velocity of the liquid flowing from the nozzle, m/sec; w_b, velocity of rise of a bubble up, m/sec; w_s, velocity of sound in a medium, m/sec; β_{exp}, experimental coefficients of mass transfer in the gas phase, $m^3/(m^2 \cdot h)$; $\beta_{exp,av}$, experimental average coefficient of mass transfer in the gas phase, $m^3/(m^2 \cdot h)$; $\beta_{g,calc}$, calculated mass-transfer coefficient, $m^3/(m^2 \cdot h)$; $\beta_{calc,av}$, calculated average coefficient of mass transfer, $m^3/(m^2 \cdot h)$; μ_g, coefficient of dynamic gas viscosity, Pa·sec; ρ_w, density of water, kg/m^3; $\rho_{w.v}$, density of water vapor, kg/m^3; ρ_{air}, density of air under operating conditions, kg/m^3; ρ_g, density of gas, kg/m^3; $\Delta\tau$, time interval within which evaporation happens, sec; φ, saturation of a layer with gas. Subscripts: d, device; w, water; w.v, water vapor; air, air; g, gas; liq, liquid; s, sound; b, bubble; op, operating; calc, calculated; n, nozzle; layer, layer; av, average; e, ejection; ex, experimental.

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