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#### HEAT AND MASS TRANSFER IN A TWISTED GAS-LIQUID LAYER

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UDC 66.021.32:536.248.2

The traditional method of organization of the processes of heat and mass transfer upon direct gas phase-liquid contact on bubble disks has definite advantages. Using this method as the basis, numerous types of heat- and mass-exchange equipment have been created which are widely used in different areas of technology [1, 2]. However, increasing the effectiveness of foam-bubble devices encounters fundamental difficulties associated with a limitation on the velocity of the gas phase.

A further development of the indicated method is the organization of the processes of heat and mass transfer in twisted gas-liquid layers formed in special vortex chambers [3-5]. According to the data of [3], the effectiveness of the transfer processes is higher in vortex gas-liquid devices than in the usual foam-bubble devices. However, one should state that there is no sufficiently reliable procedure for the calculation of heat and mass exchange in such devices.

An important stage in the creation of a procedure for the calculation of vortex gas-liquid devices is the establishment of the hydrodynamic laws of a gas-liquid layer - its structure, the rotational velocity, the average gas content, the specific contact surface of the phases (CSP), etc.

It has been established as a result of preliminary hydrodynamic investigations of a vortex gas-liquid chamber [6] that a uniform bubble structure is realized in the centrifugal force field in a twisted layer with a bubble diameter  $d$  significantly smaller than in the traditional bubble systems. The average gas content  $\varphi$  depends weakly on the velocity of the gaseous phase  $w$  referred to the total area of the guiding device. The relationship

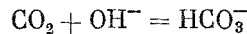
$$a = 6\varphi/d, \quad (1)$$

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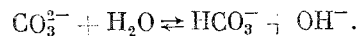
Novosibirsk. Translated from *Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki*, No. 6, pp. 129-135, November-December, 1981. Original article submitted September 26, 1980.

which relates the specific contact surface of the phases (CSP)  $a$  to  $d$  and  $\varphi$ , is valid for such a system. The direct determination of the bubble diameters in a twisted gas-liquid layer is associated with great technical difficulties and with the error introduced by the detectors positioned in the layer due to their perturbing effect on the structure being determined. Indirect determination of  $d$  is possible if the CSP is known on the assumption that the relationship (1) is satisfied. As analysis has shown [7-10], the chemical method widely used for this purpose in foam-bubble devices is most suitable for the experimental determination of the CSP. The essence of the chemical method consists of the determination of the characteristics of mass transfer in connection with absorption accompanied by a chemical reaction (chemisorption) and the establishment of a connection between these characteristics and the kinetics of the ongoing chemical reaction. Usually the reaction of the interaction of carbon dioxide gas  $\text{CO}_2$  with an alkali solution, for example,  $\text{NaOH}$ , is used for this purpose.

It is usually assumed that the interaction of  $\text{CO}_2$  with an alkali occurs according to the reaction [1]



with the subsequent rapid reaction



Thus the indicated reaction can be considered to be occurring in the first order (a reaction of pseudo-first order), for which with specific restrictions the relationship [8, 10]

$$\beta'_l = \sqrt{\bar{c}k_2D_A} \quad (2)$$

is valid, where  $\beta'_l$  is the mass exchange coefficient in the liquid phase in the case of chemisorption;  $\bar{c}$  is the average alkali concentration,  $\text{kmole/m}^3$ ;  $D_A$  is the diffusion coefficient of  $\text{CO}_2$  in the solution,  $\text{m}^2/\text{sec}$ ; and  $k_2$  is the rate constant of the chemical reaction,  $\text{m}^3/\text{kmole}\cdot\text{sec}$ . It is significant that the hydrodynamic characteristics of the system do not enter into (2). The amount of absorbed material  $M$  ( $\text{kmole}/\text{sec}$ ) can be determined from the equation

$$M = k'_l Va(c_1 - c_2),$$

where  $Va$  is the total interphase surface,  $\text{m}^2$ ,  $c_1$  and  $c_2$  are the concentrations of the absorbed component at the interface and in the mass of liquid,  $\text{kmole}/\text{m}^3$ , and  $k'_l$  is the mass transfer coefficient in the liquid phase in the case of chemisorption, including the partial coefficients of mass yield in the liquid  $\beta'_l$  and gaseous  $\beta_y$  phases:

$$\frac{1}{k'_l} = \frac{1}{m\beta_y} + \frac{1}{\beta'_l},$$

here  $m$  is the phase equilibrium constant. For an irreversible chemical reaction  $c_2 = 0$  and

$$M = k'_l a V c_1, \quad (3)$$

on the other hand the amount of material absorbed in the layer can be determined from the equation

$$M = G_{fr}(c_i - c_f)/z, \quad (4)$$

where  $z$  is the stoichiometric coefficient of the reaction,  $c_i$  and  $c_f$  are the initial and final concentrations of the solution,  $\text{kmole}/\text{m}^3$ , and  $G_{fr}$  is the flow rate of the solution,  $\text{m}^3/\text{sec}$ . If one neglects the drag of the gaseous phase, then one can assume the partial pressure of the gas at the phase interface to be equal to the partial pressure of gas in the mass; then one can determine the value of  $c_1$  from Henry's law

$$c_1 = p_{av}/mRT, \quad (5)$$

where  $p_{av}$  is the average partial pressure of  $\text{CO}_2$  in the mixture. One can determine the volume coefficient of mass transfer

$$k'_l a = \frac{M}{Vc_1} = \frac{MmRT}{Vp_{av}} \quad (6)$$

from Eqs. (3)-(5). Equations (2) and (6) are used to calculate the specific CSP.

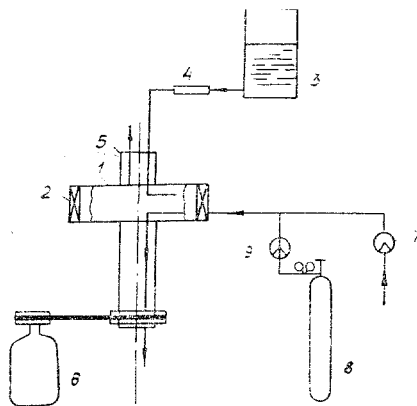


Fig. 1

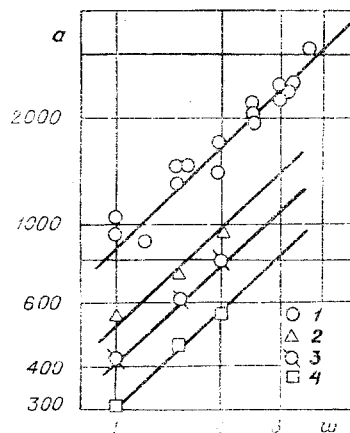


Fig. 2

The program of experimental investigations of a vortex gas-liquid chamber provided for the investigation of mass transfer in the gaseous phase, the determination of the CSP by the chemical method, and the investigation of heat exchange.

The Experimental Setup (Fig. 1). A rotating gas-liquid layer was formed in a flat vortex device 1 with shaped end walls and with a tangential gas supply through the lateral surface [5]. The inner diameter of the chamber is 200 mm, and the height of the guiding device is 47 mm. A liquid (0.5-2 N solution of NaOH in water) entered the chamber from a constant-level reservoir 3 through a calibrated capillary 4 and merged through openings in the lower cover of the device. The distance from the guiding device 2 to these openings determined the height of the bubble layer  $H$ . Dried air from a high-pressure main was combined in a specified ratio with carbon dioxide gas, which entered from the tank 8 and was fed through a guiding device to the chamber, bubbled through the liquid, and emerged into the atmosphere through the tube 5. Twisting of the layer was accomplished by the tangential input of gas to the chamber 1 and additional rotation of the chamber by a constant-current electric motor 6 with a controllable number of revolutions. The temperature of the gas and liquid before and after the device was measured with thermocouples, and the air humidity was measured from readings of dry and moist thermocouples with subsequent conversion according to a psychrometric table. The flow rate of air and  $\text{CO}_2$  was measured by the measuring disks 7 and 9, the number of revolutions of the chamber — by a frequency meter, to which the signal was fed from a circuit with a photodiode. The concentration of the solution at the entrance and exit from the device was determined by titration of selected samples of hydrochloric acid with the addition of barium chloride.

Mass Yield in the Gaseous Phase. The procedure for calculation of the CSP provides for evaluation of the diffusion drag in the gaseous phase. The mass yield coefficient in the gaseous phase  $\beta_y$  was determined in the process of desorption of water vapor from the solution into air according to the formula

$$\beta_y a = G_n p' RT / V \Delta p \mu, \quad (7)$$

where  $\rho'$  is the water density,  $\text{kg/m}^3$ ,  $R$  is the gas constant,  $\text{m}^3 \cdot \text{Pa}/\text{kmole} \cdot ^\circ\text{K}$ ,  $T$  is the average temperature of the layer,  $^\circ\text{K}$ ,  $\Delta p$  is the average logarithmic difference of the partial pressures of water vapor,  $\text{Pa}$ ,  $G_n$  is the amount of water withdrawn for humidifying the air,  $\text{m}^3/\text{sec}$ ,  $V$  is the volume of the gas-liquid layer,  $\mu$  is the molecular weight of water,

$$G_{fr} = G_i(1 - c_D c_f); \quad \Delta p = \frac{p_1 - p_2}{\ln \frac{p_* - p_1}{p_* - p_2}} = \frac{\chi p_*}{\ln \frac{1}{1 - \chi}} \quad (8)$$

$\chi$  is the humidity of the air at the exit from the layer ( $\chi_1 = 0$ ,  $p_1 = 0$ ), and  $p_*$  is the equilibrium pressure of the water vapor above the alkali solutions,  $\text{Pa}$  [12]. Data on  $k'_l \alpha$  and  $\beta'_l \alpha$  obtained in an experiment have shown that the value of the diffusion drag in the gaseous phase amounts to no more than 5% of the total mass transfer coefficient, which permits neglecting it when calculating the CSP and assuming  $k'_l \alpha \approx \beta'_l \alpha$ .

Contact Surface of the Phases. Calculation of the CSP according to Eqs. (2) and (6) is possible for specific  $\text{CO}_2$  concentrations at the phase interface. If the dependence of  $M$  on  $c_1$  is linear and passes through the origin of coordinates, then the calculation of  $\beta'_l \alpha$  from (6) and  $\beta'_l \alpha$  from (2) with a constant contact surface of the phases should fit onto a single line passing at an angle of  $45^\circ$ ; in this case

$$a = \beta'_l \alpha / \beta'_l.$$

These conditions were satisfied with  $c = 2-4 \text{ kmole/m}^3$ ,  $y = 0-12\%$ , and  $w \geq 1 \text{ m/sec}$ .

The results of the determination of the CSP are given in Fig. 2 as a function of the average discharge velocity of the gas  $w$  for different values of  $H$  and  $n$ . The points 1 are obtained with  $H = 20 \text{ mm}$ ,  $n = 350 \text{ rpm}$ , and  $G_{fr} = 6.1 \text{ ml/sec}$ , and points 2-4 were obtained for  $n = 200 \text{ rpm}$ ,  $G_{fr} = 2 \text{ ml/sec}$ , and  $H = 12, 30, \text{ and } 35 \text{ mm}$ , respectively.

An increase in the gas velocity results in a significant increase in the CSP ( $a \sim w^{0.9}$ ), whereas in ordinary bubble devices  $a \sim w^{0.3}$  [5, 13, 14].

One can explain the obtained law by the influence of centrifugal acceleration on the bubble diameter. According to (1),  $a \sim d^{-1}$ . Assuming that  $d \sim l_{ca} = \sqrt{\sigma / (g_* (\rho' - \rho''))}$  [1, 13], where  $l_{ca}$  is the capillary constant,  $\sigma$  is the surface tension,  $\text{N/m}$ ,  $\rho'$  and  $\rho''$  are the density of the liquid and gas,  $\text{kg/m}^3$ , and defining the centrifugal acceleration as  $g_* = w_{l\alpha}^2 / R_c$ , where  $w_{l\alpha}$  is the rotational velocity of the layer,  $\text{m/sec}$ , and  $R_c$  is the inner radius of the chamber,  $\text{m}$ , we obtain that  $a \sim w_{l\alpha}$ . The results of hydrodynamic investigations have permitted establishing that the rotation velocity of the layer  $w_{l\alpha}$  is uniquely related for  $n = \text{idem}$  by a linear dependence to the discharge velocity of the gas  $w$ ; therefore  $a \sim w$ , which occurs in the experiment.

The indirect confirmation of the dependence (1) has permitted using it as the basis for obtaining a generalized dependence for calculation of the CSP without resorting to an analysis of the dimensionalities of the complete system of equations. It follows from (1) that

$$ad = 6\varphi.$$

A weak dependence of  $\varphi$  on the Froude criterion  $Fr = w^2 / gh_0$  occurs in foam layers, where  $g$  is the free-fall acceleration and  $h_0$  is the height of the "clear layer" of the liquid [14]. In a centrifugal force field the characteristic linear scale (the capillary constant) depends on the value of the centrifugal acceleration, which is determined in turn by the rotational velocity of the layer; therefore there is no need to introduce this velocity in explicit form into the dimensionless relationship; then one can write the Froude criterion in the form  $Fr \sim l_{ca} / h_0$ . Taking account of what has been said, one can assume the existence of the dependence

$$al_{ca} = f(l_{ca}/h_0, \bar{g}_*),$$

where  $\bar{g}_* = g_*/g$  is the relative value of the centrifugal acceleration.

The results of the experiment to determine the CSP are presented in Fig. 3 in the coordinates  $al_{ca} (h_0 / l_{ca})^{0.3} - \bar{g}_*$ , where the solid line corresponds to a calculation by the formula

$$al_{ca} = 0.33 (l_{ca} / h_0)^{0.3} \bar{g}_*^{0.6} \quad (9)$$

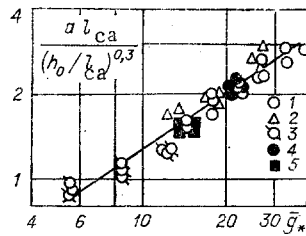


Fig. 3

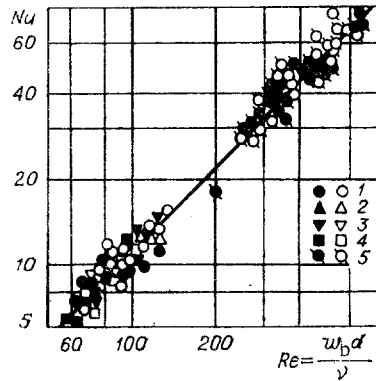


Fig. 4

which averages the experimental points to an accuracy of  $\pm 10\%$ . Formula (9) is valid in the range of variation of the parameters  $0.2 \leq l_{ca}/h_0 \leq 1.0$  and  $4.0 \leq \bar{g}_* \leq 40.0$ . Points are obtained by varying 1) the gas velocity; 2) the  $\text{CO}_2$  concentration in the gas; 3) the flow rate of the solution; 4) the number of revolutions of the chamber; and 5) the height of the foam layer. The dependence

$$ah_0 = 0.61 Fr^{0.2} W^{-0.6} \varphi^{0.3} (\mu'/\mu_{\text{H}_2\text{O}})^{0.25} \quad (10)$$

is assumed in bubble devices for calculations of the specific CSP [9, 10]. The effect of viscosity is taken into account in (10), by the factor  $(\mu'/\mu_{\text{H}_2\text{O}})^{0.25}$ , where  $\mu'$  and  $\mu_{\text{H}_2\text{O}}$  are the dynamic viscosity of the liquid being investigated and water, respectively. In our tests the value of the average gas content varied weakly, and the value of  $(\mu'/\mu_{\text{H}_2\text{O}})^{0.25}$  was practically constant (1.1-1.2). With these remarks taken into account the processing of the experimental data obtained in the coordinates (10) gave the computational dependence

$$ah_0 = 0.23 Fr^{0.18} W^{-0.47} \bar{g}_*^{0.60} \quad (11)$$

This indicates that one can calculate the specific CSP in devices with a rotating bubble layer from the equations derived for ordinary bubble devices with the addition of a factor which takes account of the effect of the twisting of the layer by an amount  $a$ . The value  $h_0$ , which depends significantly on the hydrodynamics of the process, is used in Eqs. (10) and (11) as the linear dimension. It is more preferable in this case to take the value  $l_{ca} = \sqrt{\sigma/(g_*(\rho' - \rho''))}$  as the quantity  $l$ , then the equation for calculation of the CSP is appreciably simplified; for example, one can derive Eq. (9) from (11) by replacing the quantity  $h_0$  by  $l_{ca}$ .

The set of results obtained for the dependence of the CSP on the different parameters permits drawing a conclusion about the decisive effect of centrifugal acceleration on the structure of the bubble layer and the value of the CSP. One can assume in this connection that the structural characteristics of vortex gas-liquid devices involving different ways of twisting the layer cannot appreciably alter the structure of a two-phase layer, and this means the CSP determined from Eq. (9).

Heat and Mass Transfer. The results of the determination of the temperature of the working media before and after the device were used to calculate the heat release. The thermal flux  $Q$  supplied to the gas-liquid layer was determined by the phase transition heat and convection ( $Q = Q_{pt} + Q_{con}$ ).

Upon the cooling of dry air these components of the thermal flux have a different sign, and when they are equal the temperature of the liquid is kept constant, which was realized in some tests.

The amount of heat supplied by the gas due to convection was calculated from the relationship

$$Q_{\text{con}} = wR_n c_p (t_1 - t_2).$$

where  $c_p$  is the specific heat of dry air, J/kg·°K, and  $t_1$  and  $t_2$  are the air temperature before and after the device. The heat release coefficient referred to the CSP was calculated from the formula

$$\alpha = Q_{\text{con}} / Va \Delta t,$$

where  $\Delta t$  is the arithmetic mean difference between the air and water temperatures. The results of tests on the heat and mass transfer in a gaseous phase can, with the use of the results of a determination of the CSP, be represented in the form

$$\text{Nu}_{T,D} = A \text{Re}^m \text{Pr}_{T,D}^n,$$

where  $\text{Re} = w_b d / \nu''$  is the Reynolds criterion,  $\text{Nu}_T = \alpha d / \lambda''$  and  $\text{Nu}_D = \beta_y d / D$  are the thermal and diffusion Nusselt criteria,  $\text{Pr}_T = \nu'' / \alpha''$  and  $\text{Pr}_D = \nu'' / D$  are the thermal and diffusion Prandtl criteria,  $\lambda''$ ,  $\nu''$ ,  $\alpha''$  are the thermal conductivity, kinematic viscosity, and thermal diffusivity of air,  $D$  is the diffusion coefficient of vapor in air, and  $d$  and  $w_b$  are the diameter and flotation velocity of the bubbles. The subscripts "T" and "D" correspond to the thermal and diffusion parameters. The physical properties of the gaseous phase varied insignificantly in the tests, which in this case permits excluding the effect of the Prandtl number from discussion.

The average bubble diameter was calculated from Eqs. (1) and (8), and the flotation velocity — from the formula taken from [13]:

$$w_b = \sqrt{\frac{2\sigma}{d(\rho' - \rho'')} + g_* \frac{d}{2}}.$$

The experimental results for heat and mass transfer are generalized in Fig. 4 in the coordinates  $\text{Nu}_{T,D} - \text{Re}$ , where the solid line denotes calculation from the formula

$$\text{Nu}_{T,D} = 0.105 \text{Re},$$

which averages the experimental results to an accuracy of  $\pm 15\%$ . The fact that the data on heat and mass transfer in the generalized coordinates agree indicates satisfaction of the Reynolds analogy in the case under discussion and is additional confirmation of the correctness of the cited experiment.

The data obtained for determination of the specific CSP and the heat and mass transfer in a rotating gas-liquid layer can be considered as the initial step in the creation of a more complete and rigorous procedure for the calculation of vortex gas-liquid devices, because they are obtained for a gas-liquid system whose physical properties varied within sufficiently narrow ranges. Nevertheless, the results of experiment and the analysis presented are recommended for the calculation of such devices with working media having similar physical properties.

The filled circles in Fig. 4 are obtained in experiments on an investigation of the mass yield and represent the values of the diffusion Nusselt number  $\text{Nu}_D$ , and the open circles are obtained in tests on the heat release and correspond to the thermal Nusselt number  $\text{Nu}_T$ . The points are obtained by varying 1) the gas velocity; 2) the  $\text{CO}_2$  concentration in the gas; 3) the flow rate of the solution; 4) the number of revolutions of the chamber; and 5) the height of the layer.

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NONSTATIONARY CONVECTIVE HEAT AND MASS TRANSFER IN A FLUID AT HIGH  
PECLET NUMBERS

A. D. Polyanin and P. A. Pryadkin

UDC 532.72

The diffusion flux on the surface of a drop in a stationary Stokes flow (Rybcinskii-Adamar velocity field) was determined in [1] with the help of a Laplace transformation with respect to time for the case of nonstationary diffusion with the reaction turned on suddenly. In [2-5], the self-similar variable  $\xi\delta^{-1}(t, \eta)$  ( $\xi$  and  $\eta$  are the normal and tangential coordinates fixed to the surface of the body,  $t$  is time,  $\delta$  is the thickness of the diffusion boundary layer), which permitted reducing the starting equation of convective diffusion to a first order partial differential equation for a boundary layer of thickness  $\delta$  and to an ordinary differential equation for the concentration, was used to analyze nonstationary boundary-layer problems. Two new variables (simplifying the initial problem), which were also determined by solving a first-order partial differential equation, were introduced in [5-9]. The introduction of new variables permitted studying a number of nonstationary problems, described by the equation of convective diffusion with time dependent coefficients [2-5, 7-9], for which the method in [1] cannot be used.

In the present paper, we propose a general method for solving nonstationary problems of this type, based on introducing three new independent coordinates (related to the initial coordinates by a nonsingular transformation) and permitting studying the corresponding equation in a unified form.

It is shown that in the general case of initial and boundary conditions, the solution of the boundary-layer equation has a strong discontinuity (propagating with a finite velocity) and the corresponding solution on one side of the discontinuity is determined only by the initial conditions, while on the other side (at the entrance to the diffusion bound-