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HEAT AND MASS TRANSFER BETWEEN THE DISPERSE PHASE AND THE CARRYING MEDIUM IN A PLANE TURBULENT DISPERSE NEAR-WALL JET

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UDC 66.015.23

Heat and mass transfer in a liquid–liquid and liquid–solid medium are investigated theoretically and experimentally in a jet heat- and mass-transfer apparatus.

The diagram, in principle, of an element of the construction of the jet heat- and mass-transfer apparatus under consideration is represented in Fig. 1. Clamped rigidly in the apparatus housing 1 in the shape of a parallelepiped are horizontal perforated plates 2 overlapping part of the apparatus transverse section and a moving vertical baffle 3 with slots in which horizontal plates are arranged with a certain spacing. The mentioned plates can be utilized as heat transmitting surfaces.

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Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 54, No. 6, pp. 897-904, June, 1988. Original article submitted January 27, 1987.

0022-0841/88/5406-0593$12.50

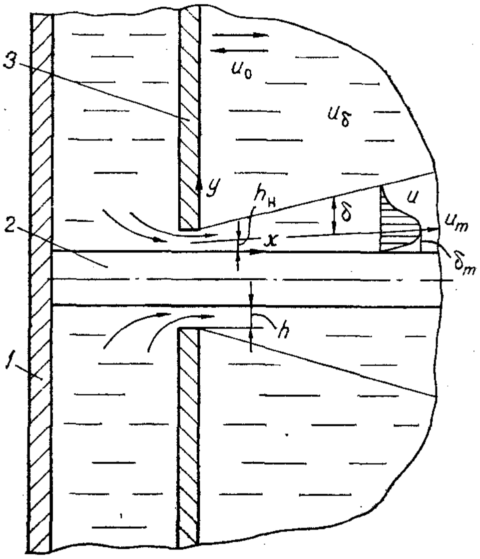


Fig. 1. Pattern, in principle, of the flow under consideration in a jet heat- and mass-transfer apparatus.

By performing reciprocating motion the baffle presses the whole volume of disperse medium in the apparatus through the slots. The disperse medium being transported through the slots by the baffle form disperse turbulent jets in which the carrying liquid medium and the disperse phase move with different velocities. A velocity gradient is also formed at the plate surfaces. These phenomena intensify the heat and mass transfer between the disperse phase and the continuous medium and the heat transport between the disperse jet and the heat-transmitting surface.

Let us examine the motion of a two-phase flow representing a two-velocity continuum [1]. We shall assume that the continuous medium is an incompressible fluid while the disperse phase is a set of droplets with concentrations n(x; y; t) whose dimensions are distributed in such a manner that the whole disperse phase can be characterized by an equivalent diameter. Interaction of the disperse phase with the carrying medium is interpreted by the existence of continuously distributed sources (sinks) of heat, mass, momentum of forces with productivity proportional to the numerical droplet concentration, in the medium. It is assumed that there is no mutual droplet interaction.

Let ϕ denote the specific volume content of the disperse phase in the carrying medium and let us write the equation of stationary motion of the carrying medium and the disperse phase as two mutually penetrating systems

$$(1-\varphi)\rho_1(v_1\nabla)v_1 = -(1-\varphi)\nabla\rho_1 + (1-\varphi)\,i\mu_1\nabla^2 v_1 + (1-\varphi)\nabla\tau_1 + (1-\varphi)\,3\pi d\mu_1(v_2-v_1)\,n, \tag{1}$$

$$\varphi\rho_2(v_2\nabla)v_2 = \varphi i\mu_2\nabla^2 v_2 + \varphi\nabla\tau_2 - 3\pi d\mu_2\varphi(v_2-v_1)\,n. \tag{2}$$

The subscript 1 refers to the carrying medium, and 2 to the disperse phase.

The system of equations is written under the assumption that the heat and mass transfer between the carrying medium and the disperse phase does not change the flow hydrodynamics of the disperse jet. Moreover, it is assumed that the partial pressure and viscosity of the disperse phase equal zero because of the high rarefaction of this system. The mechanical interaction between the carrying medium and the disperse phase is represented by a linear law of the hydrodynamic drag of the medium to droplet motion in the form of the Stokes formula.

Let us combine (1) and (2) term by term and using the obvious operational identity

$$\nabla A + \nabla B = \left(1 + \frac{B}{A}\right)\nabla A - \frac{B^2}{A}\nabla\left(\frac{A}{B}\right), \tag{3}$$

we reduce (3) to the form

$$\rho_1(v_1\nabla)v_1\left[1 + \frac{\varphi\rho_2 v_2}{(1-\varphi)\rho_1 v_1}\right] - \frac{(\varphi\rho_2 v_2^2)^2}{(1-\varphi)\rho_1 v_1^2}\nabla\left[\frac{(1-\varphi)\rho_1 v_1^2}{\varphi\rho_2 v_2^2}\right] =$$
$$= 3\pi d\mu_1 v_1 n\left(\frac{v_2}{v_1} - 1\right) - \nabla p + i\mu_1\nabla^2 v_1 + \left[(1-\varphi) + \frac{\varphi\tau_2}{(1-\varphi)\tau_1}\right]\nabla\tau_1 + \frac{(\varphi\tau_2)^2}{(1-\varphi)\tau_1}\nabla\left[\frac{(1-\varphi)\tau_1}{\varphi\tau_2}\right] \tag{4}$$

or

$$(v_1\nabla)\, v_1 = -\frac{1}{\rho^*}\nabla p + i\nu^*\nabla^2 v_1 + \frac{1}{\rho^*}\nabla\tau^*, \tag{5}$$

where

$$\rho^* = \rho_1\left[1 + \frac{\varphi\rho_2 v_2^2}{(1-\varphi)\rho_1 v_1^2}\right];\quad \nu^* = \frac{\mu_1}{\rho_1\left[1 + \frac{\varphi\rho_2 v_2^2}{(1-\varphi)\rho_1 v_1^2}\right]};$$

$$\nabla\tau^* = 3\pi d\mu_1 v_1 n\left(\frac{v_2}{v_1} - 1\right) + \left[(1-\varphi) + \frac{\varphi\tau_2}{(1-\varphi)\tau_1}\right]\nabla\tau_1 +$$

$$+ \frac{(\varphi\tau_2)^2}{(1-\varphi)\tau_1}\nabla\left[\frac{(1-\varphi)\tau_1}{\varphi\tau_2}\right] - \frac{(\varphi\rho_2 v_2^2)^2}{(1-\varphi)\rho_1 v_1^2}\nabla\left[\frac{(1-\varphi)\rho_1 v_1^2}{\varphi\rho_2 v_2^2}\right];\quad n = \frac{64}{\pi d^3}$$

After passage by the usual means [4] to a system of boundary-layer equations and obtaining integral relationships from it as is done in [2], say, (5) in projections on a rectangular coordinate system takes the form

$$\frac{d}{dx}\int_0^\delta u\,(u^{k+1} - u_\delta^{k+1})\, y^j dy = (k+1)\frac{du_\delta}{dx}\int_0^\delta y^j\,[u_\delta u^k - u u_\delta^k]\, dy - k(k+1)\int_0^\delta \frac{\tau^*}{\rho^*}\left(\frac{\partial u}{dy}\right) u^{k-1} y^j dy, \tag{6}$$

where k = 0; 1; 2; 3; 4 are integers, j = 0 is a plane jet and j = 1 an axisymmetric jet.

For $\phi = 0$ the expression (6) goes over into a known integral relation of V. V. Golubev that is utilized in analyzing turbulent jets [2]. Considering the plane disperse jet being propagated rectilinearly along a solid surface in the form of two jets [3], a near-wall jet of thickness δ_m (see Fig. 1), and a free jet of thickness δ, the passage from one jet to the other occurs along the surface on which the velocities of both jets are equal u_m, the diagrams of the turbulent friction stress rates in the near-wall jet satisfy the relationships [3]

$$\frac{u_m - u}{\sqrt{\frac{\tau^*}{\rho^*}}} = 2{,}21\ln\frac{\delta_m}{y}; \tag{7}$$

$$\tau_1 = 0.028\,\mathrm{Re}^{-0{,}25}\rho_1 u_m^2;\quad \mathrm{Re} = \frac{u_m h}{\nu_1}, \tag{8}$$

and the free part of the jet the relationships [2]

$$u = u_\delta + (u_m - u_\delta)(1 - 6\eta^2 + 8\eta^3 - 3\eta^4);\quad \eta = \frac{y - \delta_m}{\delta - \delta_m}; \tag{9}$$

$$\tau_1 = \rho_1\varepsilon\,(\delta - \delta_m)\,(u_m - u)\frac{\partial u}{\partial y};\quad u_\delta = u_0\exp(-\nu_0 x), \tag{10}$$

we represent the relationship (6) in the form of two equations for the near-wall part of the jet (j = 0; k = 0; k = 1) and one for the free part of the jet (j = 0; k = 0)

$$\frac{d}{dx}\int_0^{\delta_m} u\,(u - u_\delta)\, dy = \frac{du_\delta}{dx}\int_0^{\delta_m}(u_\delta - u)\, dy; \tag{11}$$

$$\frac{d}{dx}\int_0^{\delta_m} u\,(u^2 - u_\delta^2)\, dy = 2\frac{du_\delta}{dx}\int_0^{\delta_m}[u_\delta u^2 - u u_\delta^2]\, dy - 2\int_0^\delta \frac{\tau^*}{\rho^*}\left(\frac{\partial u}{\partial y}\right) dy; \tag{12}$$

$$\frac{d}{dx}\int_{\delta_m}^{\delta} u\,(u - u_\delta)\, dy = \frac{du_\delta}{dx}\int_0^{\delta_m}(u_\delta - u)\, dy. \tag{13}$$

Substituting the value of the velocities from (7) and (8) into (11) and (12) and integrating, we obtain

$$(Au_0 - 3k_0 A)\frac{du_m}{dx} + [u_0^3\exp(-\nu_0 x) - 3k_0^3]\frac{d\delta_m}{dx} - 4\nu_0 u_0^2\exp(-2\nu_0 x)\, k_0\delta_m + 4\nu_0 u_0^2 A\exp(-2\nu_0 x) + k_0^3; \tag{14}$$

$$A\frac{du_m}{dx}+[k_0u_0\exp(-\nu_0x)+2k_0^2]\frac{d\delta_m}{dx}+[\nu_0u_0^2\exp(-2\nu_0x)+2k_0\nu_0u_0\exp(-\nu_0x)]\delta_m; \quad (15)$$

$$\frac{d\delta}{dx}+\frac{1}{f}\left[\frac{df_1}{dx}+k_1f_3\right]\delta+\frac{f_2}{f_1}=0, \quad (16)$$

where $k_0 = \tau^*/\rho^*$; $f_1 = 14.2u_\delta^2 + 29.2u_mu_\delta - 15u_m^2$; $f_2 = 15(u_\delta - u_m)^2$; $f_3 = 0.8u_m - 0.8u_\delta$; $k_1 = \nu_0u_0\exp(-\nu_0x)$; $u_m\delta_m = A$.

The solution of the system of equations (14) and (15) has the form

$$u_m=u_{\text{н}}-\int\left(\frac{b_1}{a_1}\frac{d\delta_m}{dx}+\frac{b_2}{a_1}\right)dx; \quad (17)$$

$$\delta_m=\exp\left(-\int\frac{b_1d_1}{a_1a-Ab_1}dx\right)\left[h_{\text{н}}+\int\frac{b_2A}{a_1a_2-Ab_1}\exp\left(\int\frac{ba_1dx}{a_1aAb_1}\right)dx\right], \quad (18)$$

where

$$\frac{d\delta_m}{dx}=\frac{ba_1\delta_m}{Ab_1-aa_1}+\frac{b_2A}{Ab_1-aa_1};\ a=k_0u_0\exp(-\nu_0x);$$

$$a_1=Au_0-3k_0A;\ b=\nu_0u_0\exp(-\nu_0k)[u_0\exp(-\nu x)+2k_0];$$

$$b_1=u_0^3\exp(-2\nu_0x)-3k_0^3;\ b_2=4\nu_0u_0^2\exp(-2\nu_0x)A+k_0^3.$$

The constants of integration are found from the conditions

$$\text{for } x=0\quad \delta_m=h_{\text{н}};\ u_m=u_{\text{н}}. \quad (19)$$

The solution of (16) can be represented thus

$$\delta=\exp\left[-\int\frac{1}{f}\left(\frac{df_1}{dx}+kf_3\right)dx\right]\left\{h-\int\frac{f_2}{f_1}\exp\left[\int\left(\frac{df_1}{dx}+k_1f_3\right)dx\right]dx\right\}, \quad (20)$$

for

$$x=0\quad \delta=h. \quad (21)$$

To evaluate the reduced characteristics of the disperse stream ρ^*, τ^*, it is necessary to find the relation between the parameters ν_1 and ν_2; τ_1 and τ_2 in explicit form in a functional dependence on the coordinates.

Let us examine the acceleration of a constant-mass spherical particle subjected to Stokes hydrodynamic forces. The equation of drop motion in this most simple case can be written in such a manner:

$$\frac{dv_2}{dt}+a_0v_2=a_0v_1;\ a_0=\frac{18\mu_1}{d^2\rho_2}. \quad (22)$$

The solution of (22) has the form

$$v_2=v_1[1-\exp(-a_0t)]\ \text{for}\ t=0,\ v_2=0. \quad (23)$$

The regularity (23) obtained for the relation between the carrying medium and disperse phase velocities is valid even on the axis of the maximal jet velocity, consequently, the following relationships can also be recommended for application in the computations:

$$\tau_2=\tau_1[1-\exp(-a_0t)];\ x=u_0t. \quad (24)$$

Taken into account in the dependences obtained are changes in the coordinate of the disperse jet velocity of the medium being displaced through the baffle slots as it moves at a constant velocity in the apparatus. As the baffle motion velocity varies the complex nature of the medium displacement in the apparatus is observed. Thus, the jet is impacted on the apparatus wall in the initial phase of baffle motion, is rotated and moves behind the baffle a certain time which is difficult to reflect with high reliability in analytical dependences.

Consequently, it is recommended to draw the appropriate information necessary for the computation from experimental data. It is established that it is more convenient and simpler to take $v_2 \approx u_0$; $\nu_0 \approx 0.18$; $A = u_m h_H$; $A = 0.0038$ (u_0, h_0 are known quantities) for the first moment of the motion in evaluating the equation coefficients. In this case the measured parameters governing the motion of a turbulent disperse jet are in satisfactory agreement with the computed ones.

The solution of the hydrodynamic problem permits finding the domain of existence of a disperse jet and the velocity of the flow around the disperse phase by an external flow at any point of this jet for any time of baffle motion.

The problem of the nonstationary heat and mass transfer for translational drop motion is solved [5, 6], where the parameters that are external relative to the drop of the medium could vary in time according to a known law. It is assumed that circulation in the form of a Hill vortex is developed within the drop, and the external flow was inviscid since the flow around the drop was considered for high Reynolds numbers. This assumption becomes especially justified when the hydrodynamic layers are developed simultaneously with the temperature and concentration layers. It is considered that the boundary layer thickness is small, there are no drop surface vibrations, and chemical equilibrium is observed on the surface, and the diffusion velocity does not influence the convective rates of mass transfer. The effect of mutual drop interaction can be taken into account [6] but this encumbers the solution without justification since appropriate corrections are introduced sufficiently simply if necessary. Thus, the total heat flux from the drop to the external medium can be found from the expression [5]

$$Q = \frac{2\sqrt{\pi}\, d\lambda_1 (T_0 - T_\infty)\,\mathrm{Pe}^{0.5}}{1-\beta} J, \tag{25}$$

where

$$\mathrm{Pe} = \mathrm{Re}\,\mathrm{Pr};\quad \mathrm{Re} = \frac{ud}{\nu_1};\quad \mathrm{Pr} = \frac{\nu_1}{k_1};\quad k_1 = \frac{\lambda_1}{\rho_1 c_{p_1}};\quad \beta = \left(\frac{\lambda_2 c_{p_2}\rho_1}{\lambda_1 c_{p_2}\rho_2}\right)^{0.5};$$
$$J = \frac{\sqrt{3}}{4}\int_0^\pi \frac{\sin^3\Theta\, d\Theta}{\left[(f-\cos\Theta) - \frac{1}{3}(f^3 - \cos^3\Theta)\right]^{0.5}}, \tag{26}$$

for $t \to \infty$ $J = 1$,

$$f = \frac{1 - \dfrac{1-\cos\Theta}{1+\cos\Theta}\exp\left(-\dfrac{3}{2}\mathrm{Pe}\,\tau\right)}{1 + \dfrac{1-\cos\Theta}{1+\cos\Theta}\exp\left(-\dfrac{3}{2}\mathrm{Pe}\,\tau\right)};\quad \tau = \frac{k_1 t}{(0.5a)^2}. \tag{27}$$

The temperature of the drop surface will equal

$$T_K = T_\infty + \frac{T_0 - T_\infty}{1+\beta}. \tag{28}$$

The total mass flow from the drop to the medium is determined from the expression

$$G = \frac{4\sqrt{\pi}\, RD_1 (c_0 - \alpha_1 c_\infty)\,\mathrm{Pe}_1^{0.5}}{1+\beta_1} \cdot J, \tag{29}$$

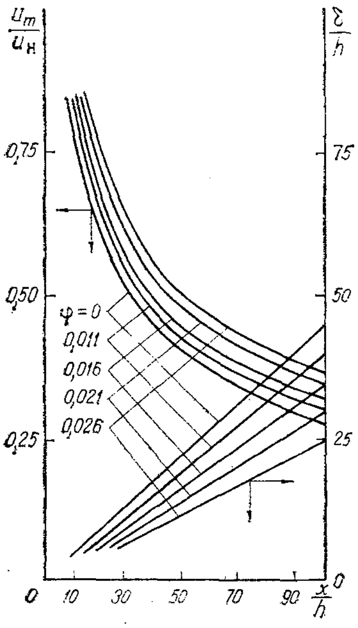
where $\beta_1 = \left(\frac{D_1}{D_2}\right)^{0.5}$; $\mathrm{Pe} = \frac{ud}{D_1}$; $\mathrm{Sc} = \frac{\nu_1}{D_1}$.

Substance concentration on the drop surface is constant but undergoes a discontinuity during passage through the surface. From the outer side it equals

$$c_{K_1} = c_\infty + \frac{c_0 - \alpha_1 c_\infty}{\alpha_1 + \beta_i},$$

and from the inner $c_{k_2} = \alpha_1 c_{k_1}$.

It is shown in [5] that the nonstationary phenomena damp out for $ut/0.5d \approx 1$ upon a sudden change in the temperature or concentration in the external medium, i.e., lasts 100th



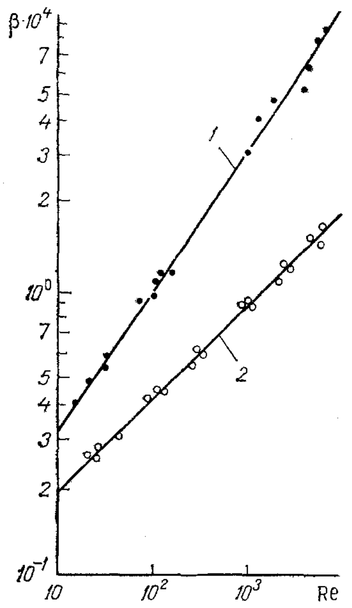


Fig. 2 Fig. 3

Fig. 2. Dependence of the change in the maximal velocity and thickness of the jet along the length on a specific volume content on the disperse phase in the jet u = 10.8 m/sec, h = $11 \cdot 10^{-3}$ m, u_0 = 0.25 m/sec.

Fig. 3. Dependence of the heat- and mass-transfer coefficients in the disperse jet on the Reynolds number; 1) Sc = 1390; 2) Pr = 0.7. $\beta \cdot 10^4$ m/sec.

of a second, say, in a liquid–liquid extractor (d = 10^{-3} m, u = 3-5 m/sec). The jet development in the apparatus under consideration is realized during several tenths of a second and more, consequently, the heat and mass transfer process in the jet apparatus can be considered practically stationary.

The further course of the computation is determined by problems that are solved by the researcher. If there is the possibility of measuring the change in concentration in a drop in one period of baffle travel, then the validity of the solution obtained for the hydrodynamic problem is verified directly by means of (28) by substituting the values found for the velocities into the Péclet criterion in all sections of baffle motion. If there is no such possibility, then integrated measurements at the input and output should be used, and the theoretical computational formulas obtained from the results of the solutions should be corrected by coefficients assuring satisfactory agreement between the computation and the parameter measurements in their experimentally investigated range.

The velocity fields and jet contours are measured in a 400-mm-diameter tube with a piston to which reciprocating motion in the vertical plane is transmitted by rods from the driver. A 25-mm-wide and 300-mm-long slot was along the piston diameter. A 3-mm-thick and 294-mm-wide steel strip is placed vertically at the center of the slot. A turbulent disperse near-wall plane jet was formed during piston motion.

Electroanemometer sensors were fastened to the piston with the possibility of moving the fastenings along the piston radius, as well, respectively, the sensors along the length of the fastenings perpendicularly to the piston surface. Water at a 10°C temperature was used as carrying medium and river sand as the disperse phase. The disperse phase was moved from up downward along the tube at a 0.03-m/sec velocity. The maximal distance from the piston at which the velocity fields and jet contours were measured was 1 m. The maximal jet velocity was measured most confidently (the relative error did not exceed 3-4%), the remaining measurements yielded a relative error up to 32%.

Computations to the graph in Fig. 2 were performed by using (17) and (20). No experimental values of these parameters are presented since the curves of changes in the parameters are placed close to each other and the spread in the experimental data is sufficiently great, which makes perception of the graph difficult. The following values of the initial data were used in the computations: $\rho_1 = 10^3$ kg/m³; $\rho_2 = 2.3 \cdot 10^3 \cdot$kg/m³; $\mu_1 = 102.4 \cdot 10^{-6}$(kg·sec)/m²; $d = 2.1 \cdot 10^{-3}$ m; $u_0 = 0.25$ m/sec; $u_H = 10.8$ m/sec; $\varepsilon = 0.014$; $h_H = 0.3 \cdot 10^{-3}$ m; $h = 1.1 \cdot 10^{-3}$ m; $A = 0.0038$ m²/sec; $t = 2c$; $\nu_0 = 0.18$ m⁻²; $\alpha_1 = 0.86$; $x = 0.5$ m.

As is seen from Fig. 2, a rise in the disperse phase content raises the long-range capability of the jet and makes it narrower.

Mass transfer in a disperse turbulent near-wall jet in the liquid−liquid system was investigated during the extraction of benzoic acid from water by toluene. In the operating principle the experimental apparatus was identical to the hydrodynamic test stand described, and its geometric dimensions are the following: tube diameter is 40 mm, piston slot width and length are 2.5 and 30 mm, respectively, and the gap between the vertical plate and the slot walls is 1.1 mm.

The influence of the escape velocity and time of jet formation on the extraction process proceeding in the turbulent jet is determined, all other conditions being equal, by the magnitude of the Reynolds number found by the relative velocities of the medium and the disperse phase. Represented in Fig. 3 are values of the mass-transfer coefficient over the continuous medium (the drag in the disperse phase equals zero in practice) for different Reynolds numbers. The quantity of extracted substance per unit time was determined from the measured concentrations of benzoic acid at the water flow input and output and the coefficient of mass transfer in the continuous medium was determined through the interphasal surface. The following initial data were used in the computations using (28): $\rho_1 = 0.986 \cdot 10^3$ kg/m³; $\rho_2 = 0.865 \cdot 10^3$ kg/m³; $\phi = 0.22$; $\mu_1 = 0.95 \cdot 10^{-3}$ Pa·sec; $\alpha = 1.1 \cdot 10^{-3}$ m; $u_0 = 0.1$-0.8 m/sec; $\varepsilon = 0.014$; $h_H = 0.3 \cdot 10^{-4}$ m; $h = 1 \cdot 10^{-4}$ m; $\nu_0 = 0.18$ m⁻¹; $A = 0.0038$ m²/sec; $\alpha_1 = 0.86$; $x = 0.5$ m; $c_\infty = 0$; $D_1 = 0.72 \cdot 10^{-9}$ m²/sec; $D_2 = 2.4 \cdot 10^{-9}$ m²/sec; $c_0 = 20$ kg/m³.

As is seen from Fig. 3, the mass-transfer coefficient in the domain of rapid formation of turbulent disperse jets in time is raised by almost an order, other conditions being equal. The β does not exceed $0.7 \cdot 10^{-4}$ m/sec in the best modern pulsating mixer-settler extractors.

The heat transfer between the carrying medium and the disperse phase in a turbulent disperse near-wall jet was investigated in a gas−solid system. The disperse phase (river sand heated to different temperatures) was introduced into a turbulent near-wall air jet emerging into an air space with the same temperature (19°C), and the change in temperature in the jet was determined by using a thermocouple. The heat elimination coefficient was determined by the quantity of the disperse phase introduced, the interphasal surface, the sand temperature. The following data were used in the computations: $\rho_1 = 1.25$ kg/m³; $\rho_2 = 2.3 \cdot 10^3$ kg/m³; $\mu_1 = 1.81 \cdot 10^{-6}$ (kg·sec)/m²; $\phi = 0.09$; $d = 1.2 \cdot 10^{-3}$ m; $u_0 = 0$; $\varepsilon = 0.014$; $h_H = 5 \cdot 10^{-3}$ m; $A = 0.0038$ m²/sec; $\alpha = 0.86$; $\lambda_2 = 0.31$ kcal/(m·deg·h); $T_0 = 503$ K; $T_\infty = 292$ K; $\lambda_1 = 0.021$ kcal/(m·deg·h); $c_{p_1} = 0.24$ kcal/(kg·deg); $c_{p_2} = 0.26$ kcal/(kg·deg).

The contact time of the disperse phase with the carrying medium was determined by means of (23) by knowing the distance from the slot to the section in which computations were performed for the maximal velocity point and the parameters over the jet section. Measurement of the temperature and velocity fields of the jet permitted obtaining all the necessary information in a broad range of Reynolds numbers from one experiment.

It follows from Fig. 3 that as the relative velocity increases the Reynolds numbers grow, and therefore, other conditions being equal the heat elimination coefficient is raised. Attention is turned to the high values of the heat elimination coefficient from the dispersed phase in a turbulent flow with a time-varying jet velocity. Computations were carried out by means of (25).

NOTATION

v, velocity of disperse medium motion; ∇, Hamilton operator; ρ, mass density; P, pressure; μ, dynamic viscosity; ν, kinematic viscosity; i, single event; τ, turbulent friction stress; d, particle diameter in the flow; n, number of particles (drops); ϕ, specific volume content of the disperse phase in the carrying medium; u, velocity of the continuous medium flow around the disperse phase; u_δ, velocity in the space to which the jet escapes; u_0, velocity of baffle motion; u_H, initial jet velocity in the slot; ε, coefficient of free jet turbulence; h_H, height of the near-wall jet in the initial section; h, slot height; T_0, initial disperse jet temperature; T_∞, temperature of the environment; k, coefficient of thermal diffusivity;

T_k, temperature of the disperse phase; λ, coefficient of heat conduction; D, diffusion coefficient; c_k, concentration on the drop surface; c_p, specific heat; c_∞, substance concentration in a medium.

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MODEL OF THE FLOW IN A CIRCULAR JET DEVELOPING IN A CROSS STREAM. SOLUTION OF THE INITIAL LENGTH PROBLEM

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UDC 532.517.4

A flow model and an integral method of calculating the initial length of a circular jet in a cross stream are proposed. The results of calculating the characteristics of the initial length are in satisfactory agreement with the experimental data.

As is known (see [1-7]), the flow in a jet issuing at an angle to the main stream has a complex three-dimensional character and differs significantly from the flow in a submerged jet or a jet in a cocurrent stream. The jet in a cross stream is distinguished from ordinary jet flows by the presence of a flow velocity component normal to its trajectory. Obviously, it is this velocity component that must be considered "responsible" for the particular characteristics of the flow over the jet and the jet's development. Thus, the complex pattern of pressure distribution on the underlying surface around the jet, which to some extent is qualitatively similar to the pressure distribution around a cylinder, depends, for a given jet velocity, on the cross stream velocity component normal to the jet trajectory, the underpressure beyond the jet and along its sides being proportional to the velocity head created by this velocity component. This results in radial pressure differences which must obviously lead to the appearance of secondary flows in cross sections of the jet which, in their turn, cause the experimentally observed deformation of the cross section.

The mechanism of ejection of fluid by the jet from the surrounding space must also be more complex than in ordinary jets. On the one hand, the jet develops as in a cocurrent flow, and in accordance with the hypothesis of plane sections the cocurrent flow velocity may be assumed to be equal to the component of the cross stream velocity in the direction of the jet trajectory. The mass ejected by a jet in a cocurrent flow is known to be proportional to the difference of the jet and cocurrent flow velocities. On the other hand, the flow normal to the jet trajectory must contribute to the mass added to the jet, since for this flow the jet is, as it were, a fluid-filled space and at the edge of the jet an additional mixing zone must be formed. The mass entering this mixing zone from the cross stream is entrained by the jet, from which it acquires a longitudinal momentum, and becomes, as it were, part of the jet. This mixing zone increases from the plane of symmetry towards the sides of the jet and thereby causes its lateral thickening.

Since as the cross stream velocity increases the additional ejection into the jet becomes more intense, while the length of the part of the jet on which the additional ejection takes place decreases, at a certain value of the jet/flow velocity ratio there must

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0022-0841/88/5406-0600$12.50