4. Farrell and Johnson, "The mechanism of heat exchange in the evaporation zone of a heat pipe," in: Heat Pipes [Russian translation], Mir, Moscow (1972), pp. 9-32.
5. Layman and Huang, "Analysis of the temperature distribution in the wicks of heat pipes," in: Heat Pipes [Russian translation], Mir, Moscow (1972), pp. 175-202.
6. R. Gregorig, "Hautkondensation an feingewellten Oberflächen bei Berücksichtigung der Oberflächenspannungen," Z. Angew. Math. Phys., 5, No. 1, 36-49 (1954).
7. A. P. Solodov and V. P. Isachenko, "Investigation of heat transfer in the condensation of steam on finely corrugated pipes," in: Heat Exchange and Hydraulic Resistance. Transactions of the Moscow Power Institute [in Russian], Issue 63 (1965), pp. 85-95.
8. N. V. Zozulya, V. P. Borovkov, and V. A. Karkhu, "Filmwise condensation of steam on a finely ribbed surface," in: Problems of Technical Thermal Physics [in Russian], Naukova Dumka, Kiev (1968), pp. 3-7.
9. A. R. Dorokhov, "Experimental investigation of the heat exchange in the condensation of moving Freon-21 vapor on horizontal pipes," Author's Abstract of Ph. D. Thesis, Institute of Thermal Physics, Siberian Branch of the Academy of Sciences, Novosibirsk (1975).
10. G. G. Shklover, O. O. Mil'man, V. L. Baskov, and G. A. Ankudinov, "Some peculiarities of heat exchange in the condensation of steam on horizontal finely corrugated pipes," in: Heat Exchange and Hydrodynamics [in Russian], Nauka, Leningrad (1977), pp. 174-180.
11. F. Roseberry, Handbook of Vacuum Engineering and Technology [Russian translation], Énergiya, Moscow (1972).

MASS TRANSFER FROM THE WALL TO THE STREAM OF AN AXISYMMETRIC FLUID JET

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UDC 532.62

The results of measurements are presented pertaining to friction and mass transfer during interaction of an axisymmetric vertical one-phase or two-phase fluid jet and a horizontal plane wall.

In technological processes of surface-chemical treatment of materials, one now uses more extensively progressive methods where the active fluid is force fed to the surface, particularly in the form of jets. The laws governing this method of treatment as, e.g., in dimensional etching of metallic surfaces are, however, little known.

The hydrodynamics and the mass transfer in the case of a single axisymmetric one-phase fluid jet impinging on a plane barrier have already been theoretically analyzed in great detail [1, 2]. Theoretical relations have been derived [2] for determining the local hydrodynamic frictional stresses τ in all principal flow regions in this setup and calculating the mass-transfer coefficient β in the region of laminar flow. In the same study [2], the theoretical relations were verified experimentally by the electrodiffusion method. Unlike the flow pattern in [1, 2], real processes of metal dissolution include also an evolution of hydrogen in the form of bubbles so that the fluid medium becomes a two-phase system and, furthermore, solutions are often fed to the treated surface from below. Under these additional conditions, i.e., in the presence of a gaseous phase subject to forces of gravity in the stream these factors do not influence the hydrodynamics and the mass transfer in an obvious manner. Meanwhile, however, it is well known that in some flow patterns such as the one studied by other authors [3], introduction of a gaseous phase in the form of bubbles contributes to an appreciable intensification of the mass-transfer processes.

In this study the authors have experimentally verified the validity of theoretical conclusions arrived at earlier [2] in the case of a fluid jet impinging on a wall from below, and at the same time examined the effect of a gaseous phase on the hydrodynamics and the mass-transfer processes.

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In the course of this study, by the electrodiffusion method, the frictional shearing stresses τ at the wall and the mass-transfer coefficient β were measured. The latter were compared with those measured in the case of dissolution of natural specimens. The experiments involving the electrodiffusion method were performed with the apparatus and according to the procedure thoroughly described in the earlier study [2]. In this case τ and β were measured in a one-phase as well as in a two-phase stream, with the jet of electrolyte (0.1 N ferri—ferrocyanide solution in distilled water + supporting 5% NaOH) fed to a disk 400 mm in diameter from a nozzle below through an orifice 10 mm in diameter. The longitudinal jet axis was oriented normally to the plate. The distance from the nozzle throat to the plate was maintained constant and equal to 24 mm in all experiments. Measuring probes were built into the disk flush with the surface: platinum probes 0.3 mm in diameter for measuring τ and nickel probes 2 mm in diameter for measuring β. The diffusion coefficients D and the kinematic viscosity under the conditions of these experiments were, respectively, $7.13 \cdot 10^{-10}$ and $0.94 \cdot 10^{-6}$ m²/sec.

Measurement of the mass-transfer coefficient β by dissolution of natural specimens was done at disks 400 mm in diameter and 4 or 6 mm thick. These disks were made of the grade MA-8 magnesium alloy. A separate solution of sulfuric acid in distilled water was prepared for each specimen. The concentration of hydrogen ions in the solution was measured by titration and also calculated from the amount of acid (chemically pure condition at delivery) which had been added to a fixed volume of water. Depending on the temperature of the water and the acid prior to their mixing, the initial concentration of hydrogen ions in the various experiments varied from 350 to 430 g-eqiv/m³. The diffusion coefficient for hydrogen ions was $D_H = 9.34 \cdot 10^{-9}$ m²/sec [4] and the kinematic viscosity was $\nu = 0.905 \cdot 10^{-6}$ m²/sec.

Magnesium and sulfuric acid were selected as the pair of substances for this study, because dissolution of magnesium in sulfuric acid had been found to be effected by the diffusional mechanism [5]. In the case of the MA-8 alloy the authors verified it by the "revolving disk" method in a solution of said concentration.

Some of experiments involving measurement of the mass-transfer coefficient β by etching of natural specimens were performed with the jet flowing verically downward. In this case the distance from the nozzle throat to the wall was 100 mm. The temperature (25°C), the concentration of reacting ions, and the flow rate of the electrolyte did not vary by more than 1% during all experiments, but the concentration of hydrogen ions during dissolution of natural specimens varied within 3%. For the experiments with a two-phase jet there was a bubble generator in the form of a porous hollow cylinder installed inside the nozzle system. The diameter of bubbles was 300 μm, approximately corresponding to their size during dissolution of the metal. The length of the etching period was established on the basis of minimum change in the concentration of hydrogen ions in the solution and practical feasibility of measuring the results. After etching, a rinsed and dried specimen was gauged for thickness determination along five or six radii drawn from the critical point (on the jet axis). The thickness was measured with an indicator having 0.01-mm divisions on the scale. The thickness readings at points equidistant from the center were averaged so as to compensate for the initial thickness nonuniformity as well as for random deviations.

For calculating β in this case the well-known relation [6]

$$\beta = I/zFSc \tag{1}$$

was used with I denoting the current across the reacting surface (here during dissolution); z, valence of ions participating in the reaction (here $z_H = 1$ and $z_M = 2$); S, surface area involved in the reaction; and c, concentration of hydrogen ions.

The expression for the current I was based on the relations for the mass rate of flow according to Faraday's laws

$$q = I/zFS \tag{2}$$

and for the amount of dissolved metal

$$q = V\rho/A_M tS \tag{3}$$

with V denoting the volume of dissolved metal ($V = S\Delta$); Δ, thickness of the etched away layer

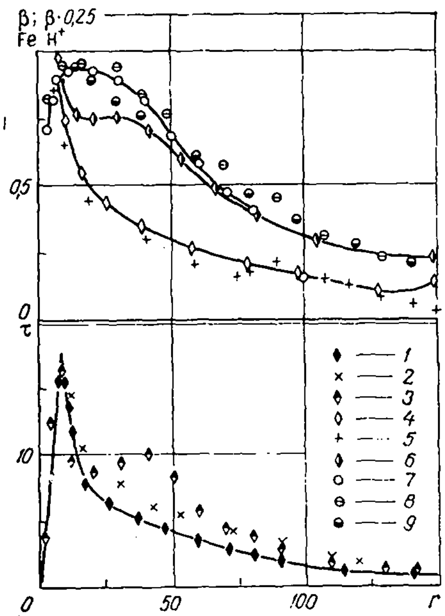

Fig. 1

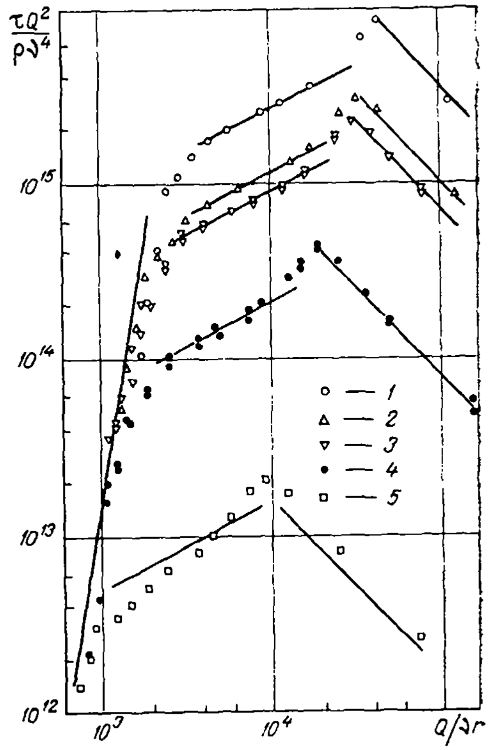

Fig. 2

Fig. 1. Variation of τ and β along the radius of jet spreading under various experimental conditions: 1, 2, 4, 5, 7, 8) without injection of gas; 3, 6, 9) with gas injected at rates 2.1, 0.6, $2.5 \cdot 10^{-5} m^3/sec$, respectively; 2, 5, 8) jet flowing downward; 7, 8, 9) experiments with natural specimens; 2, 5) data in [2].

Fig. 2. Generalized results of τ measurements at various flow rates of the fluid (m^3/sec): 1) 32; 2) 24.3; 3) 22.4; 4) 14; 5) $6.9 \cdot 10^{-5}$.

of metal; ρ, density of the metal; A_M, atomic weight of the metal; and t, dissolution time.

Equating the right-hand sides of expressions (2) and (3) yields the current

$$I = V\rho F z_M / A_M t \tag{4}$$

and insertion of expression (4) into expression (1) yields

$$\beta = \Delta\rho z_M / A_M t z_H c_H. \tag{5}$$

For our case of magnesium dissolving in sulfuric acid we have

$$\beta = 0.143\Delta / c_H t. \tag{6}$$

The experiments were performed with flow rates of the fluid $Q = (6.9\text{–}32.0) \cdot 10^{-5}\ m^3/sec$. Measurements were made in all zones of viscous flow. The same system of flow analysis was used here as in the previous study [2]. It ought to be noted that no zone of hydraulic "jump" and thus also no trail behind such a jump appear in the case of jet impinging on a plate from below. Here within the "jump" region the stream separates from the plate, forming droplets and individual jets.

Composite graphs of local τ and β values determined according to various methods and under various different experimental conditions but for the same flow rate of $14 \cdot 10^{-5}\ m^3/sec$ are shown in Fig. 1. These graphs (points 1, 2, 4, 5) indicate that the trend of τ and β values does not depend on the direction of jet flow. The maximum τ and β values, just as in the previous study [2], occur within the region of the critical point $r \leqslant 1.6 r_0$ (r_0 denoting

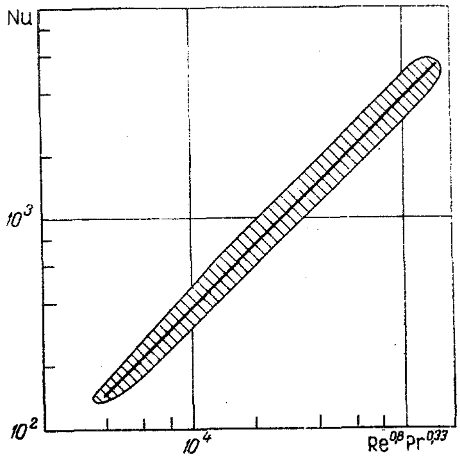

Fig. 3. Generalized results of mass-transfer measurements at flow rates of the fluid ranging from 6.9 to $32 \cdot 10^{-5} m^3/sec$ and gas injection rates ranging from 0.35 to $3.33 \cdot 10^{-5} m^3/sec$.

the jet radius within the impact zone). Some discrepancy with the results in [2] is evident in β measurements behind the point of merger of the boundary layer and the main stream ($r > r_+$) where [2]

$$r_+ = 0.257 r_0 (Q/\nu r_0)^{1/3}. \quad (7)$$

According to the graph (point 5), the value of β begins to increase beyond r = 75 mm and at r = 90 mm it exceeds that at r = 75 mm by ≈ 30%. This increase of β becomes larger with increasing flow rate of fluid and reaches 40% at $Q = 28.3 \cdot 10^{-5}$ m^3/sec [2]. In the previous study [2] this anomaly was explained by formation of a wave pattern before the hydraulic jump. The presence of waves contributes to intensification of the mass transfer. In our case, as been said already, there occurs no hydraulic jump and thus no wave pattern develops with the attendant β-anomaly.

The results of τ measurements in all flow zones at various flow rates of electrolyte are shown generalized in dimensionless coordinates [2] in Fig. 2.

The close agreement between results of τ measurements and theory [2] (straight lines in Fig. 2) as well as the identical trendof τ and β values (points 1, 2, 4, 5) indicate that in the case of an axisymmetric one-phase fluid jet impinging on a plate from below the theoretical relations in [2] are valid throughout almost the entire region of viscous flow.

For plotting the straight lines in Fig. 2 the surface velocity U_S of the stream was calculated more precisely, by also taking into account the loss of jet energy due to bending through a 90° angle [7]. According to that calculation, $U_S = 0.9U_0$ and the numerical coefficients in the expressions for τ [2] must be changed to

$$\tau Q^2/\rho\nu^4 = 0.0687 (Q/\nu r)^{7/2} (r/r_0)^{9/2}, \quad (8)$$

for the region of the critical point and

$$\tau Q^2/\rho\nu^4 = 0.0875 (Q/\nu r_0)^3 (Q/\nu r)^{1/2} \quad (9)$$

for the flow region where U_S = const ($r_+ \geqslant r > 1.6 r_0$).

For the flow region beyond the merger point there remains valid the asymptotic approximation [2]

$$\tau Q^2/\rho\nu^4 = 2.9 \cdot 10^{-2} (Q/\nu r)^5. \quad (10)$$

In expressions (8) and (9)

$$r_0 = (Q/\pi U_0)^{1/2}, \quad (11)$$

$$U_0 = \sqrt{(Q/\pi r_c^2)^2 \pm 2gh}. \quad (12)$$

Here r_c is the radius of the nozzle orifice, h is the height, the "+" sign refers to downward flow and the "-" sign refers to upward flow of the jet.

As the graph in Fig. 2 indicates, relations (8) and (9) fit the experimental data better than do the corresponding relations in the previous study [2], where the discrepancy between measurements and theory was ≈ 10%.

On the diagram in Fig. 1 are also shown (points 3, 6) the results of τ and β measurements, respectively, with injection of a gaseous phase into the stream. Experiments with injection of a gaseous phase into the stream of electrolyte were performed for the purpose of studying the feasibility of intensification of the mass transfer under "extrinsic problem" conditions and explaining the role of that gaseous phase in real processes of dimensional etching.

The volume flow rate of the gaseous phase injected into the stream in various experiments was varied from $0.35 \cdot 10^{-5}$ to $3.5 \cdot 10^{-5}$ m^3/sec, corresponding to a gas content of α = 1-30 vol. %. According to the graph in Fig. 1, injection into the stream of a gaseous phase in the form of air bubbles causes the frictional shearing stresses as well as the mass-transfer coefficient to increase by an amount which can reach 100-200% in the U_S = const region. Both τ and β increase with a higher gas content, but for every flow rate of the fluid there is a singular value of α beyond which a range of self-adjointness with respect to α exists. This value is α = 15% for $Q = 14 \cdot 10^{-5}$ m^3/sec and α = 4% for $Q = 28.3 \cdot 10^{-5}$ m^3/sec. We note that the effect of a gaseous phase is weak in the region of the critical point.

According to the data in Fig. 1, the mass-transfer coefficient is also in the case of dissolution (points 7, 8) much higher than as measured by the electrodiffusion method (4, 5) and closer to its value in the case of a two-phase jet (points 6). Under the given conditions, moreover, the rate of metal dissolution with gas evolution is the maximum possible. Indeed, injection of an additional gaseous phase (α = 20-30%) has no effect on the intensity and the mode of mass transfer (points 9 in Fig. 1). We note, furthermore, that near the critical point the effect of artificially injected bubbles on the mass transfer is not identical to the effect of hydrogen bubbles evolving as a result of the chemical reaction.

Results of measurements made in a two-phase jet by the electrodiffusion method and by etching of natural specimens are shown in Fig. 3 in generalized coordinates. These data pertain to the U_S = const flow region and fit, within satisfactory accuracy, the relation (solid line)

$$\mathrm{Nu} = 0.038 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.33}, \tag{13}$$

where

$$\mathrm{Re} = U_S r / \nu. \tag{14}$$

Expressions of the (13) kind have been derived elsewhere [8, 9] for turbulent flow under "intrinsic problem" and "extrinsic problem" conditions, respectively. Accordingly, gas evolution in the process of dimensional etching as well as artificial injection of a gaseous phase in the form of bubbles cause the transfer processes during interaction of a jet and a wall to become turbulent.

NOTATION

A, atomic weight; c, concentration, g-equiv/m^3; D, diffusion coefficient, m^2/sec; F, Faraday constant, C/g-equiv; I, current, A; Q, flow rate, m^3/sec; S, surface area involved in the reaction, m^2; V, volume, m^3; β, mass-transfer coefficient, m/sec; Δ, thickness of the etched away layer, m; g, acceleration due to gravity, m/sec^2; h, height (static head), m; q, mass flow intensity, g/m^2 · sec; ν, kinematic viscosity, m^2/sec; ρ, density, g/m^3; t, time, sec; τ, frictional shearing stress, N/m^2; and z, electric charge of an ion.

LITERATURE CITED

1. E. Watson, "Radial spread of a liquid jet over a horizontal plane," J. Fluid Mech., 20, 481-499 (1964).
2. V. E. Nakoryakov, B. G. Pokusaev, E. N. Troyan, and S. V. Alekseenko, "Flow of thin fluid films," in: Wave Processes in Two-Phase Systems [in Russian], Izd. Inst. Tekh. Fiz., Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1975), pp. 129-206.
3. A. P. Burdukov, N. V. Balukina, and V. E. Nakoryakov, "Flow characteristics of gas–liquid mixtures with bubbles at low values of the Reynolds number," Zh. Prikl. Mekh. Tekh. Fiz., No. 4, 137-141 (1975).

4. J. Heurowski and J. Kuta, Principles of Polarography [Russian translation], Mir, Moscow (1965).
5. Ya. V. Durdin and Z. U. Dukhnyakova, "Parallel studies of dissolution rates and dissolution potentials of magnesium and manganese," in: Collection of Articles on General Chemistry [in Russian], Vol. 1, Moscow—Leningrad (1953), pp. 157-162.
6. V. G. Levich, Physicochemical Hydrodynamics, Prentice-Hall (1962).
7. I. E. Idel'chik, Handbook of Hydraulic Drag [in Russian], Gosénergoizdat, Moscow—Leningrad (1960).
8. D. A. Frank-Kamenetskii, Diffusion and Heat Exchange in Chemical Kinetics, Princeton Univ. Press (1955).
9. K. O. Bennet and D. E. Mayers, Hydrodynamics—Heat Transfer—Mass Transfer [Russian translation], Nedra, Moscow (1966).

TRANSVERSE STABILITY OF A LIQUID JET IN A COUNTERFLOWING AIR STREAM

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The development of small perturbations which bend a liquid jet in a counterflowing air stream is analyzed here. It is demonstrated that the most dangerous perturbations of the jet axis have a spatial distribution, and the increment of perturbation buildup is calculated.

Straight jets of a liquid moving in air at sufficiently high velocities are unstable against transverse perturbations [1-4]. As a consequence, they acquire a waviness and eventually break up. The problem of dynamic action of an air stream on the a priori unknown surface of a jet with a flow also yet to be determined is a very difficult one and, for this reason, only the first steps have so far been taken toward a theoretical description of it [2, 5, 6].

Here will be analyzed the stability of a straight laminar jet of a viscous liquid against small long-wave spatial perturbations. The analysis will be based on the equations of dynamics of thin liquid jets [7], which in the case of small perturbations are

$$
\begin{gathered}
\frac{\partial f}{\partial t}+f_0\frac{\partial V_\tau}{\partial s}=0,\\
\rho f_0\frac{\partial \mathbf{V}}{\partial t}=\frac{\partial}{\partial s}\left(P\boldsymbol{\tau}+\mathbf{Q}\right)+\mathbf{q},\\
\rho\frac{\partial \mathbf{K}}{\partial t}=\frac{\partial \mathbf{M}}{\partial s}+\boldsymbol{\tau}\times\mathbf{Q},\\
\mathbf{K}=I\left(\mathbf{n}\Omega_n+\mathbf{b}\Omega_b\right),\quad \Omega_n=-V_{b,s}-\varkappa V_n,\quad \Omega_b=V_{n,s}-\varkappa V_b,\\
\mathbf{M}=3\mu I\left[\mathbf{n}\left(\Omega_{n,s}-\varkappa\Omega_b\right)+\mathbf{b}\left(\Omega_{b,s}+\varkappa\Omega_n\right)\right]-\alpha I a_0^{-1}k\mathbf{b}+\mathbf{M}_1,\\
P=3\mu f_0\frac{\partial V_\tau}{\partial s}+\pi a\alpha+\alpha f_0\frac{\partial^2 a}{\partial s^2}+P_1.
\end{gathered}\tag{1}
$$

In the selected reference system the unperturbed jet remains at standstill while the air stream moves along its axis. The cross section of the jet is assumed to be circular, without body forces and rotation of the liquid about the jet axis ($\Omega_\tau = 0$).

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