ELECTROCHEMICAL MEASUREMENT OF FRICTION IN TWO-PHASE FLOWS

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The total pressure drop for adiabatic two-phase flow in a channel of constant section is given by the formula [1]

$$\Delta p = \Delta p_f + \gamma_+ h + \{\gamma'' \, (\varphi_2 W_2''^2 - \varphi_1 W_1''^2) + \gamma'[\,(1 - \varphi_2)W_2''^2 - (1 - \varphi_1)W_1''^2]\} \tag{1}$$

Here φ is the true gas content, Δp_f is the frictional resistance, $\gamma_+ h$ is the gravity force term, and γ_+ is the specific weight of the mixture, which depends on φ. The expression in the braces accounts for the acceleration losses.

For the experimental determination of Δp_f we must know φ, and the methods for measuring φ [2, 3] do not yield reliable results over a wide range of variation of the gas content in the flow.

The simplest approximation for calculating Δp_f is the homogeneous model, according to which

$$\Delta p_f = c_f \frac{\gamma_+ W_+^2 L}{2gd} \tag{2}$$

Here W_+ is the reduced mixture velocity, c_f is the friction coefficient of the homogeneous flow [1], d and L are the diameter and length of the channel, respectively. The relation proposed by Lockhart and Martinelli [4] is also widely known.

Under more complex conditions, for example unsteady flow of a two-phase stream, there are no methods for calculating the quantity Δp_f.

In the following we describe results of measurement of the tangential stresses on the channel wall for isothermal steady and unsteady flow of a two-phase stream using the electrochemical method. This method was developed previously by Hanratty [5] for a single-phase fluid and was also developed in [6]. The idea of the method lies in measuring the limit diffusion current in an electrolytic cell consisting of the electrolyte flowing in the channel, a large electrode (anode), and a polarized annular sensor (cathode). The electrolyte is an 0.001-0.15 N aqueous solution of ferri-ferrocyanide with a background 2N solution of Na(OH). In the limit diffusion current regime the electrochemical reaction rate is determined only by the mass transfer intensity between the cathode surface and the electrolyte stream. The connection between the mass flux and the limit current I is expressed by the relation

$$q = I \,/\, Fz \tag{3}$$

Here F is the Faraday number, z is the number of transferred electrons. For large Prandtl numbers (P = 2430 in the case in question) the diffusion boundary layer thickness for sufficiently small sensor dimension is much less than the thickness of the viscous sublayer. Then Landau's assumption [7] on linear dependence of the longitudinal velocity component and the transverse coordinate y is valid

$$u = \tau_w y \,/\, \mu \tag{4}$$

Here τ_w is the tangential wall stress, and M is the dynamic viscosity. The solution of the diffusion boundary layer equation [5, 6] yields the connection between τ_w and I

$$\tau_w = \frac{1{,}85\mu I^3}{z^3 F^3 l^2 h^3 D^2} \left(\frac{A}{c_\infty} \right)^3 \tag{5}$$
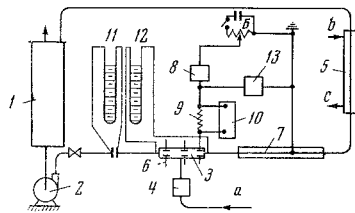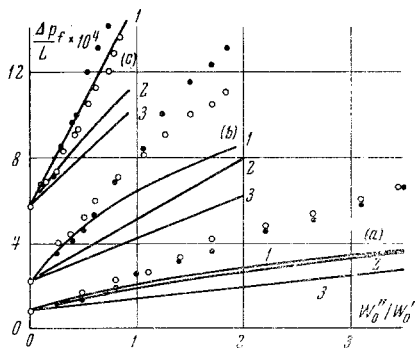
Fig. 1

Fig. 2

Here A is the molecular weight of $K_3Fe(CN)_6$, c_∞ is the bulk electrolyte concentration, D is the diffusion coefficient, l is the streamwise longitudinal dimension of the sensor, and h is the sensor width.

Formula (5) is valid for two-phase flow if there is a continuous liquid film on the channel wall.

The experiments were conducted on horizontal and vertical tubes using two different setups.

A schematic of one setup (for a horizontal tube) is shown in Fig. 1. Both setups consist of closed circulation loops consisting of the stainless steel centrifugal pump 2, combination reservoir and separator 1, gas and liquid flow meters, and stabilization segments. Only vinyl plastic or plexiglass pipes were used in the loop. Pure nitrogen was used as the light phase (arrow a shows gas input) to avoid oxidation of the electrolyte by oxygen in the air and also because the decomposition potentials of oxygen and ferricyanide are very close. The liquid temperature was maintained at 25° C with the aid of a water cooler 5 (arrows b and c denote water in and out). The temperature of the two-phase medium was measured at the entrance to and exit from the test section by copper — constantan thermocouples to within 0.1° C.

The effect of temperature on τ_w is very significant, since the viscosity and the diffusivity depend on temperature. The diffusivity data were taken from [8], and we measured the viscosity in the temperature range from 17 to 35° C.

The test section 3 was made in the form of a plexiglass tube of diameter d = 11.2 mm and length L = 100 mm. Nine electrochemical sensors were spaced at 5-10 mm intervals along the length of the tube. The sensors were made in the form of 0.2 and 0.5 mm thick nickel strip rings. The gas-liquid mixture was created by blowing gas through a porous tube (d = 11.2 mm) located three diameters from the first sensor.

Particular attention was devoted to careful finishing of the working surface of the sensors. A check of the sensor performance was provided by calibration conducted by comparing the values of the electrochemical measurement of τ_w with the pressure drop measurement and the values of τ_w calculated using the well-known theoretical relations for different values of the Reynolds number R for a single-phase fluid.

The coefficient accounting for inaccuracy of the measurement of the working surface length for each sensor remained constant over the entire R range from 10^4 to $1.2 \cdot 10^5$. The anode 7, made from the same nickel strip, was located downstream. The measurement circuit included a 4-V, 10-20-Ω dc source. The magnitudes of the regulated voltage and the limit current in the circuit were measured by the voltmeter 13 and milliammeter 8 respectively.

The measurement of the ferricyanide ion concentration in the solution was made by potentiometric titration.

In the experiments on the vertical tube (d = 15 mm) the sensors were 0.5 and 3 mm long and were located 1 mm apart. Their indications of the value of τ_w agreed. The gas-liquid mixture was created in a mixer at a distance of 150 diameters from the first sensor by injecting gas through a porous plate or through a nozzle.

In the slug flow regime the true velocity of the gas phase was assumed equal to the slug velocity and was determined from the time for passage of a single slug between two point electrodes. In this case the true gas content was calculated using the formula

$$\varphi = W_0'' / W'' \qquad (6)$$

Here W'' is the velocity of the slugs, W_0'' is the reduced velocity of the gas phase.
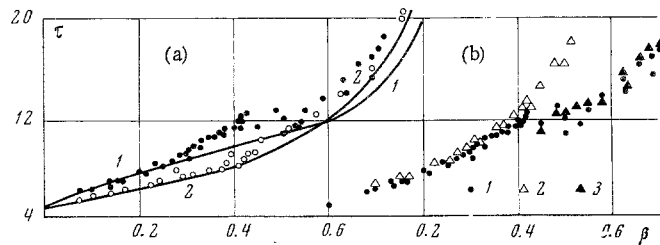
Fig. 3

Figure 2 shows the results of experiments for unsteady two-phase flow in a horizontal tube, presented in the form of $\Delta p_f/L$ in $(N/m \cdot m^2)$ as a function of the dimensionless reduced gas velocity W_0''/W_0'; the light circles are the averaged values of indications of nine electrochemical sensors, the dark circles are the experimental data on static pressure drop; regions (a), (b), and (c) correspond to the liquid velocities $W_0' = 2.8$, 4.13, 8.06 m/sec. The friction losses were determined using the formula

$$\Delta p_f/L = 4\tau_w/d \tag{7}$$

We see that the values of $\Delta p_f/L$ measured from the pressure drop lie above the values obtained by the electrochemical method. This discrepancy is explained by the fact that the acceleration losses are not taken into account in the first method. Curves 1, 2, 3 show the results of frictional resistance calculations by the Lockhart-Martinelli method [4], using the homogeneous model, and using the recommendations developed at the TsKTI (Central Boiler and Turbine Institute) [9].

Analysis of the experiments and calculations shows that the method of [4] yields good agreement with experiment for the velocity $W_0' = 8.06$ m/sec. This method gives results which are too low at lower reduced liquid velocity for values of $W_0''/W_0' > 0.8$.

Calculations using the homogeneous model and using the TsKTI standards give good agreement with experiment.

Results of experiments on the vertical tube for a reduced liquid velocity of 1.1 m/sec are shown in Fig. 3a, b in the form of τ_W in (N/m^2) as a function of the volumetric gas content discharge β. In the case of gas injection through the porous plate the transition from the bubble flow regime to the slug flow regime occurred for $\beta \approx 0.43$, while for gas injection through the nozzle the transition occurred for $\beta \approx 0.1$.

In Fig. 3 the points are the experimental (electrochemical) results; the light points are for injection through the nozzle, the dark are for injection through the porous plate; curve 1 is the calculation after Lockhart-Martinelli, curve 2 is for the homogeneous model. We see from the figure that the friction is higher in the bubble regime than in the slug flow regime.

Figure 3b shows the friction data obtained by the electrochemical method for injection through the porous plate, and also the values calculated using the formula

$$\tau_w = \frac{d}{4L}[\Delta p - \gamma'L(1-\beta)] \tag{8}$$

Here Δp is the measured static pressure drop.

In Fig. 3b the points 1 are for the electrochemical calculation, points 2 are the calculation using β and Δp, points 3 are the calculation using φ and Δp. We see from the figure that for $\beta \sim 0.43$ (in the slug flow regime) the discrepancy between the values of τ_W measured by the different methods is large. The difference disappears if in (8) we use in place of β the value of φ found from (6).

LITERATURE CITED

1. S. S. Kutateladze and M. A. Styrikovich, Hydraulics of Gas-Liquid Systems [in Russian], Gosenergo-izdat, Moscow (1968).
2. A. A. Armand, "Resistance in flow of two-phase system in horizontal tubes," Izv. Vses. teplotekhn. in-ta, No. 1 (1946).
3. H. S. Isbin, N. C. Sher, and K. C. Eddy, "Void-fractions in two-phase steam water flow," A. I. Ch. E. Journal, No. 3, No. 1 (1957).

4. V. L. Streeter, Handbook of Fluid Dynamics. McGraw-Hill Book Company, New York (1961), pp. 3-17.

5. I. Mitchell and J. Hanratty, "A study of turbulence at a wall using an electrocemical wall shear stress meter," J. Fluid Mech., Vol. 26, pt. 1 (1966).

6. S. S. Kutateladze, V. E. Nakoryakov, A. P. Burdukov, and V. A. Kuz'min, "Application of electrochemical method for measuring friction in the hydrodynamics of two-phase media," collection: Proceedings of 3rd All-Union Conference on Heat and Mass Transfer [in Russian], Vol. 2, p. 367, Minsk (1968).

7. A. D. Landau and E. M. Lifshits, Mechanics of Continous Media [in Russian], Gostekhizdat, Moscow (1954).

8. A. I. Arvia, S. L. Marchiand, and I. I. Podesta, "The diffusion of ferrocianid and ferricianid jons in aqueous solutions of potassium hydroxide," Electrodynamica Acat, Vol. 12, p. 259. Pergamon Press Ltd., Northern Ireland (1967).

9. Standards for Calculating Water Circulation in Steam Boilers [in Russian], Mashigz, Moscow—Leningrad (1950).