EXPERIMENTAL INVESTIGATION OF HORIZONTAL TWO-PHASE FLOW BY AN ELECTRODIFFUSION METHOD

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The results of an experimental investigation of the local mean and fluctuating friction at the wall of a horizontal tube are presented for the case where a gas–liquid stream flows in the tube with a wide range of regime parameters. The electrodiffusion method is used for measuring the friction. Curves of the tangential stresses along the perimeter of the tube as well as along its length are constructed, permitting an objective determination of certain flow regimes. The experimental results are compared with those of the existing computational methods.

At present, of all the existing methods only the "floating" element enables one to measure the mean friction at a wall directly. This method has a number of significant drawbacks: nonlocal nature, inertia, and perturbation of the basic flow.

In the present work the electrodiffusion method is used for the measurement of the tangential stresses in an isothermal gas–liquid flow; the essential features of this method are discussed in detail in [1, 3]. At large Prandtl numbers (Pr > 1000) in the case of circular sensor electrodes the friction is calculated from the formula

$$\tau = \frac{3.2\mu I^3}{F^3 d^5 D^2 c_\infty^3} \tag{1}$$

where F is the Faraday number, μ, D, c_∞ are the physical constants of the electrolyte, and I is the value of the measured limiting current in the electrochemical cell including a sensor cathode of diameter d, an

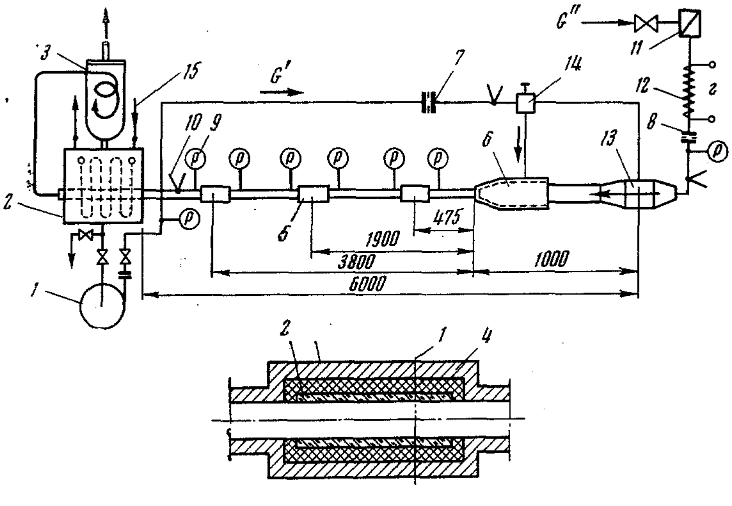

Fig. 1

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TABLE 1

V_0', m/sec	$G' \cdot 10^5$, kg/sec	β	$G'' \cdot 10^5$, kg/sec	No. of measurements
0.1	29.3	0.348÷0.999	(1.73÷3450)	330
0.25	73.75	0.206÷0.998	2.12÷5200	396
0.5	146.5	0.13÷0.993	2.5÷5420	900
1.0	293	0.107÷0.98	4.34÷3530	1036
2.0	586	0.03÷0.903	2.42÷1020	1207
3.0	880	0.02÷0.87	2.5÷1000	600
4.0	1172	0.01÷0.8	2.5÷500	400

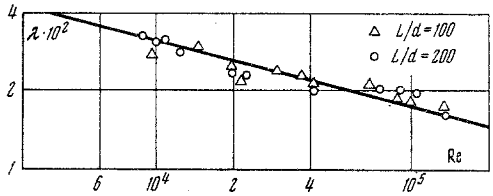


Fig. 2

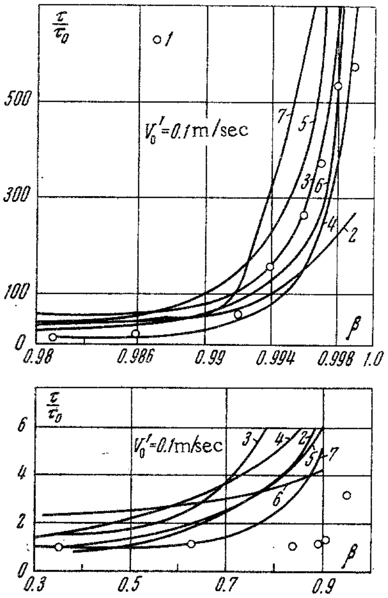


Fig. 3

anode of large surface, and the electrolyte. A weak solution of ferric-ferrocyanide in 0.5 N aqueous solution of NaOH was used as the electrolyte. Only an inert gas, nitrogen, was used in the experiments in order to avoid oxidation of the electrolyte by oxygen. The procedure of operation with this electrolyte has been discussed in detail in [2, 3]. The theoretical possibility of using the electrodiffusion method for measuring friction in a two-phase flow was demonstrated in [2] taking the example of the standard "projectile" regime of flow. The first results on the measurement of friction for a significantly nonstationary horizontal gas–liquid flow were also obtained in [2].

The investigation of the flow of two-phase streams in a horizontal tube is complicated by their significant asymmetry caused by the force of gravity. This results in a large diversity of flow regimes compared to the vertical flows. For example, for certain discharge rates of the liquid and the gas in a horizontal tube a stratified flow regime may exist, where the liquid lies mainly in the lower half of the channel. Therefore, in the study of such flows there arises a problem of measuring their local characteristics not only along the length of the channel but also along its perimeter. On the other hand, the presence of such information enables one to refine the classification of the flow regimes of these systems. The program of the present experiment included the following:

1) measurement of the mean and the pulsating friction both along the length of the channel and along its perimeter. The range of variation of the flow rates of the liquid and the gas and also the number of measurements for each velocity of the liquid are given in Table 1;

2) measurement of the total pressure drop at different distances from the entrance to the channel.

The experiments were conducted in a horizontal tube with inner diameter equal to 19 mm and length 6 m at pressures close to the atmospheric pressure.

The equipment, whose schematic diagram is shown in Fig. 1, consisted of a circulating loop for the liquid which included: tank 2 with 0.25 m^3 capacity, centrifugal pump 1, closed-delivery conduit of 50 mm diameter with built-in flow-rate-measuring equipment 7, mixing chambers 6 and 13 at the entrance to the channel, and an experimental segment 6 m in length. The separation of the gas and the liquid was done in the tank only in separator 3 of cyclone type. The flow rate of the liquid was regulated by remote control

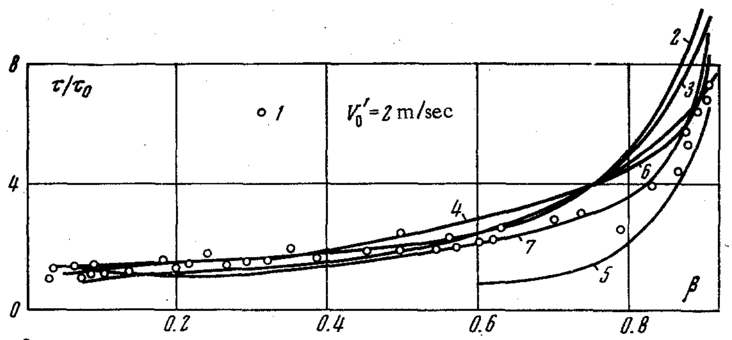


Fig. 4

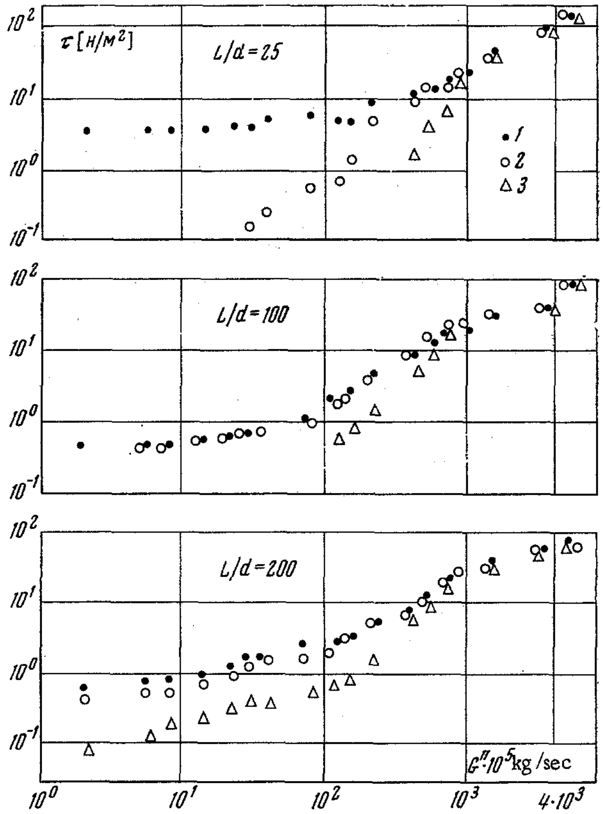
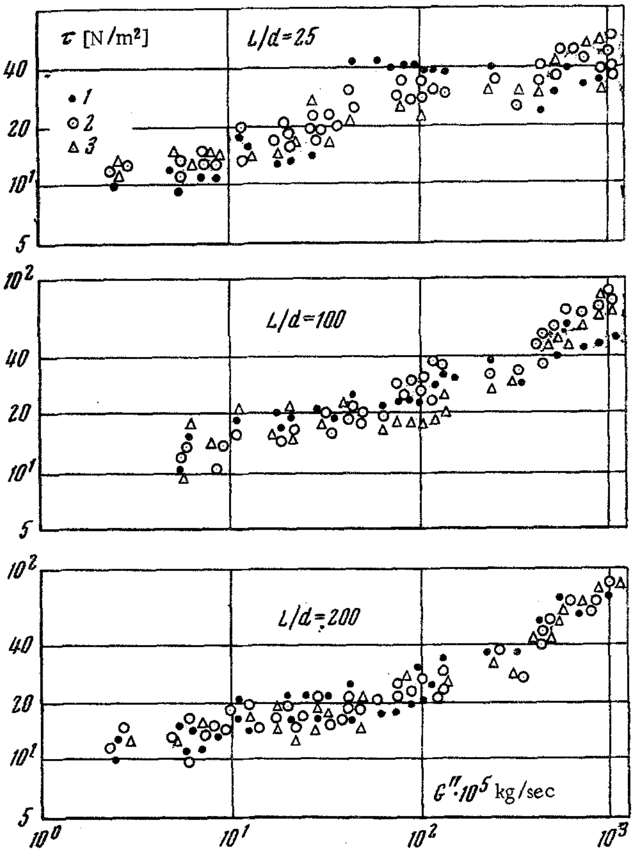


Fig. 5

of the number of rotations of the electric motor of the pump, regulating valves, and nozzle-type mixer 6. The temperature of the liquid was maintained constant in the range 20-27°C by using water cooler 16. The gas (nitrogen) was humidified and cleaned in filter 11 and was heated to t=t' in 1 kW electric heater 12 and entered the mixer chambers 13 or 6.

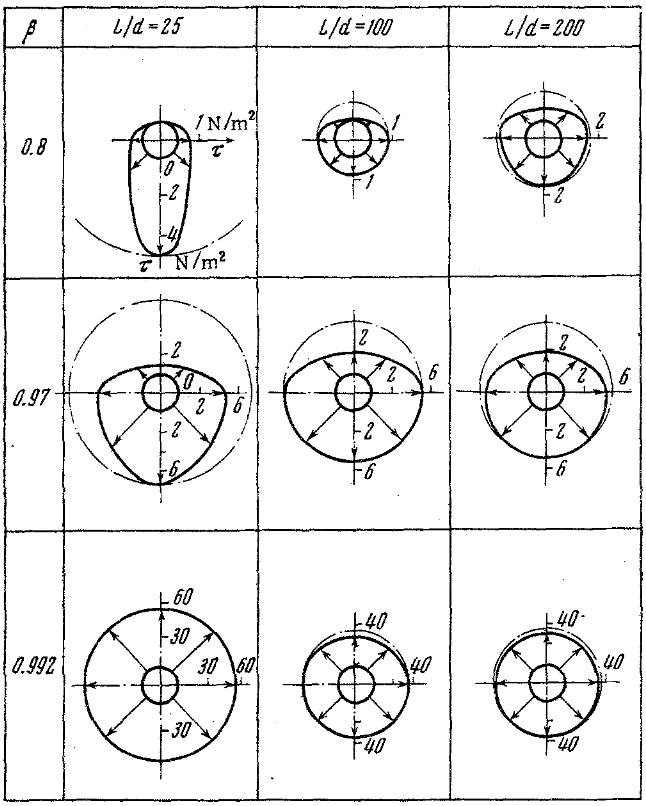
The gas–liquid mixture was produced either in chamber 13, where the liquid and the gas were mixed at an angle of 90°, or by blowing the gas through nozzle 6. In the latter case the liquid entered uniformly along an annular slit whose thickness was varied with an accuracy of 0.01 mm. This accuracy was necessary for the investigation of the annular regime of the flow. The pressure was sampled in six cross sections of the experimental tube along its length, so that the total pressure drop is 5 m and also so that the local pressure drops at 25, 100, and 200 guages from the entrance could be measured. The flow rates of the liquid and the gas, and also the pressure drops, were measured with five U-shaped manometers.

The experimental segments of measurement of local friction were placed at distances of 25, 100, and 200 gauges from the entrance. The construction of the sensors is shown schematically in Fig. 1. Twelve platinum electrodes 1 of 0.5 mm diameter were embedded in glass sleeve 2 along its perimeter, which was



τ [N/m²]
L/d=25
L/d=100
L/d=200
1
2
3
40
20
10¹
5
10²
G''·10⁵ kg/sec
10⁰
10¹
10²
10³

Fig. 6



β
L/d=25
L/d=100
L/d=200
0.8
0.97
0.992
N/m²
τ

Fig. 7

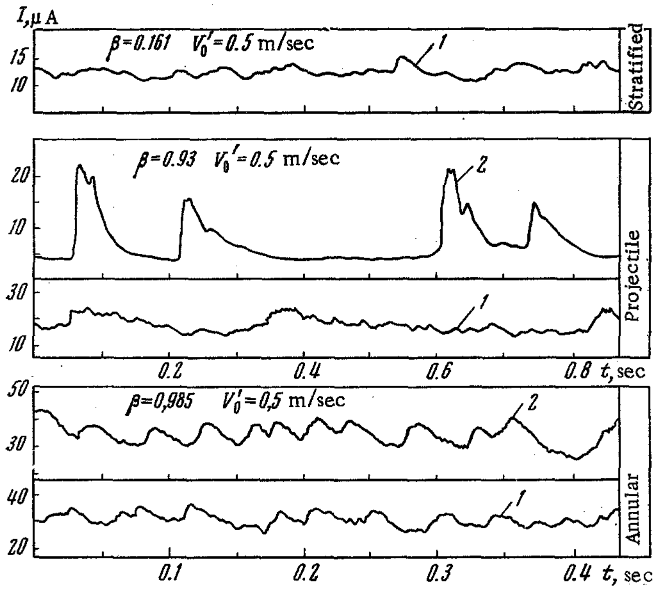


Fig. 8

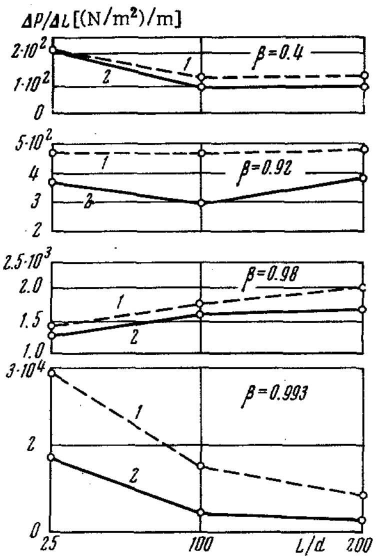


Fig. 9

filled with epoxy resin 3 in the frame of the segment. The sensors were carefully ground flush with the wall of the channel according to the scheme described earlier [2, 3].

Experiments conducted with a single-phase flux showed good agreement of the results of measurement of the friction coefficient with those computed from the well-known Blasius formula for Reynolds numbers $R = 8 \cdot 10^3 - 1.5 \cdot 10^5$ (Fig. 2).

The results of measurement of friction in the flow of the gas–liquid stream for liquid velocities $V_0' = 0.1$ and 2 m/sec are shown by the open circles 1 in Figs. 3 and 4 in $(\tau/\tau_0, \beta)$ coordinates. Here, τ_0 is the friction during the flow of the pure liquid, β is the volume gas content computed from the local parameters of the flow, and τ is the friction of the two-phase flow averaged over 12 sensor readings in the section $L/d = 200$ gauges from the entrance. As evident, the friction increases significantly with the flow rate of the gas; for example, for $V_0' = 0.1$ m/sec the increase is from $\tau/\tau_0 \approx 1$ for the stratified regime to $\tau/\tau_0 \approx 600$ for the fully developed annular regime. Here and below, we adhere to the common classification of flow regimes for horizontal two-phase flows. In the stratified regime τ was computed taking into consideration the friction of the gas at the nonwetted surface of the tube.

A comparison of the experimental results with those obtained from well-known computational methods is also shown in Figs. 3 and 4; here line 2 pertains to the computation by TsKTI (Central Scientific-Research, Design, and Planning Institute for the Boiler and Turbine Industry) method [4], line 3 pertains to the homogeneous model [5] based on the assumption of absence of slip between the phases [here R is computed from the velocity of the mixture, while the viscoity μ_+ is computed from the formula

$$\frac{1}{\mu_+} = \frac{1}{\mu''}x + \frac{1}{\mu'}(1 - x)$$

where μ', μ'' are the viscosity of the liquid and gas, respectively, x is the gas content of the flow by weight], and line 4 pertains to A. A. Armand's formula [6]

$$\frac{\tau}{\tau_0} = \frac{C}{(1 - 0.833\beta)^{1.75}} \quad \text{при}\ \beta < 0.9\ ;$$

for $\beta > 0.9$ the constant before β is equal to 1. The straight line 5 gives the computation by Becker's method [7]; line 6, by the Lokart–Martinelli method; and line 7, by the Nelson–Martinelli method [7] based on a