HYDRAULIC RESISTANCE OF ANNULAR, AND DISPERSE-ANNULAR FLOW CONDITIONS OF A TWO-PHASE MIXTURE

V. V. Permyakov and A. M. Podsushnyi

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Results of experimental research on hydraulic resistance in the case of annular and disperse-annular systems of movement of a two-phase mixture are given.

Annular, and disperse-annular conditions of two-phase flow are encountered in various heat-exchange equipment. In spite of the large number of works devoted to determination of the resistance in such flows, there have so far been no theoretical relationships which would determine the resistance in a well-defined manner as a function of the initial conditions.

The relationships in [1, 2], for example, do not take into account the influence of surface tension.

We have carried out research on the hydraulic resistance in the case of annular, and annular-disperse conditions of movement of a two-phase mixture in a horizontal tube of diameter 19 mm. Before it enters the working section, the air passes through a stabilization section, whose length is 1000 mm. The liquid is introduced through an annular opening in the tube wall.

The static pressure variation was measured through holes of diameter 1 mm on the face of the tube; these holes were located at a distance of 30, 445, 1017, and 1609 mm from the liquid inlet point. The pressure drop was measured by differential manometers filled with water. The tubes leading to them were filled with air, the tubes for selecting pressure were connected to settling chambers; differential manometers were connected to the upper part of these, and liquid was blown through periodically from below.

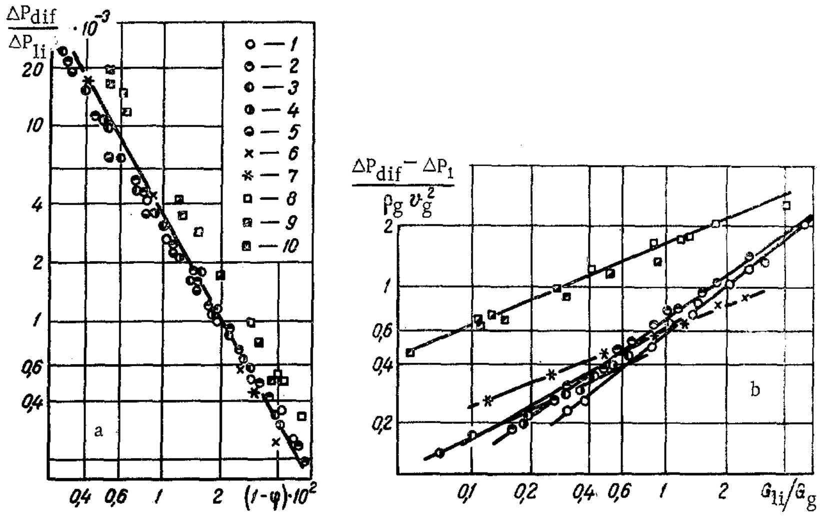

Fig. 1. Relationships $\Delta P_{dif}/\Delta P_{li} = f(1-\varphi)$ (a) and $(\Delta P_{dif}-\Delta P_l)/\rho v_g^2 = f(G_{li}/G_g)$ (b). Water: 1) $v_g = 35$ m/sec; 2) 60; 3) 80; 4) 100; 5) 130; kerosene: 6) $v_g = 35$ m/sec; 7) 60; transformer oil: 8) 35; 9) 60; 10) 80.

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TABLE 1. Physical Properties of the Liquids Used

Liquid	$\rho_{li}\cdot 10^{-3}$, kg/m^2	$\mu_{li}\cdot 10^3$, N·sec/m^2	$\sigma\cdot 10^3$, N/m
Water	1	1,006	72,7
Kerosene	0,786	1,55	25,7
Transformer oil	0,87	19,8	29,6
Glycerol solution I	1,198	79	61
Glycerol solution II	1,17	37,8	62
Glycerol solution III	1,158	18,6	62,8

The physical characteristics of the liquids used are given in Table 1.

The results of measurements of the pressure drop between the cross sections, at a distance of 1017 and 1609 mm from the liquid input point are given below.

The experimental data obtained for the pressure drop for movement of gas (without liquid) agree with an accuracy of ±5% with the Darcy–Beisbach formula

$$\Delta P_1 = \lambda \frac{l}{d} \frac{\rho_g v_g^2}{2}, \tag{1}$$

where λ is the resistance coefficient, which is determined by the Blasius formula for $\mathrm{Re} < 10^5$

$$\lambda = \frac{0.3164}{\mathrm{Re}^{0.25}} \tag{2}$$

and according to the Nikuradze formula for $\mathrm{Re} > 10^5$

$$\lambda = 0{,}0032 + \frac{0.221}{\mathrm{Re}^{0.237}}. \tag{3}$$

In Fig. 1a the results of experiments to determine the resistance in the case of movement of a gas–liquid flow are given in the coordinates proposed by Armand [2]. The actual gas content by volume φ was determined from formulae obtained in [2]:

$$1-\varphi = \frac{4+\frac{8}{7}m}{5+m\left(\frac{\beta}{1-\beta}+\frac{8}{7}\right)}, \tag{4}$$

$$m = 4\,\mathrm{Re}_{li}^{1/8}\sqrt{\frac{\gamma_g}{\gamma_{li}}}\left[0.69+(1-\beta)(4+21.9\sqrt{\mathrm{Fr}})\right]. \tag{5}$$

The straight line plotted according to the Armand formula is also given here for comparison:

$$\frac{\Delta P_{dif}}{\Delta P_{li}} = \frac{1.73}{(1-\varphi)^{1.64}}. \tag{6}$$

It is seen from the graph that the data for water are described satisfactorily by formula (4). The experimental points for kerosene and transformer oil are not generalized by the relationship (4), since this relationship does not take into account the surface tension and it does not adequately represent the influence of viscosity through the pressure losses of one phase.

We have represented the pressure drop in the gas–liquid phase (to generalize the experiments) in the form of the sum of the pressure drop ΔP_1 for the gas flow with the same gas density and derived speed as in two-phase flow, and the pressure drop ΔP_2 caused by the presence of liquid:

$$\Delta P_{dif} = \Delta P_1 + \Delta P_2. \tag{7}$$

The experimental data are processed in the form of the relationship

$$\frac{\Delta P_{dif}-\Delta P_1}{\rho v_g^2} = f\left(\frac{G_{li}}{G_g}\right). \tag{8}$$

Fig. 1b shows the experimental data described in formula (8).

The straight lines which generalize the experimental points for liquids in which the surface tension is less than that of water have a less marked slope. The experimental points for kerosene in the case of small relative discharges of G_{li}/G_g are located higher than the similar points for water.

The viscosity of the liquid has an influence in this region. In the case of large relative discharges the experimental points for kerosene are located lower; this is associated with the influence of surface tension. A similar relationship has already been noted [3].

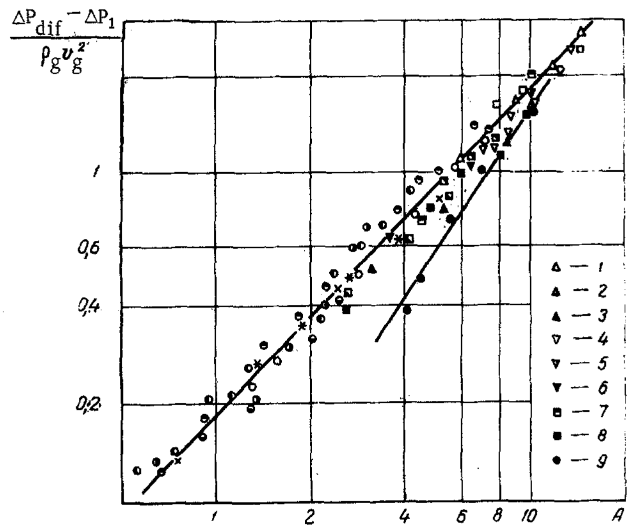

Fig. 2. Relationship $(\Delta P_{dif} - \Delta P_1)/\rho v_g^2 = f(A)$, $A = l/d \cdot (\mu_{li}/\mu_g)^{0.3}(G_{li}/G_g)^{0.67}(\mu_{li} v_g/\sigma)^{-0.21}$: glycerol solution I: 1) $v_g = 35$ m/sec; 2) 60; 3) 80; glycerol solution II: 4) $v_g = 35$ m/sec; 5) 60; 6) 80; glycerol solution III: 7) $v_g = 60$ m/sec; 8) 80; water–air: 9) experimental data of Magiras and Dukler [4]; remaining designations see Fig. 1.

All the experimental data can be generalized with an accuracy of ±20% by the relationship

$$\frac{\Delta P_{dif} - \Delta P_1}{\rho v_g^2} = 5.84 \cdot 10^{-3} \frac{l}{d} \left(\frac{\mu_{li}}{\mu_g}\right)^{0.3} \left(\frac{G_{li}}{G_g}\right)^{0.67} \left(\frac{\mu_{li} v_g}{\sigma}\right)^{-0.21} \qquad (9)$$

The influence of the criterion $\mu_{li} v_g/\sigma$ in our experiments is limited to the numerical value of 20. When $\mu_{li} v_g/\sigma > 20$ it is therefore necessary to substitute $\mu_{li} v_g/\sigma = 20$ into relationship (9):

$$0.49 < \frac{\mu_{li} v_g}{\sigma} < 129; \quad 55.5 < \frac{\mu_{li}}{\mu_g} < 4350;$$

$$0.042 < \frac{G_{li}}{G_g} < 5.3; \quad 35 < v_g < 130 \text{ m/sec.}$$

The limit of variation of G_{li}/G_g and v_g includes both the annular and disperse-annular systems.

Our experimental data, processed according to formula (9) and [4] are given in Fig. 2. Some deviation of the values is possible; this is associated with the different diameters of the tubes used in the experiments.

NOTATION

l and d	are the length and diameter of the tube, m;
v_g	is the derived gas speed, m/sec;
ρ	is the density, kg/m^3;
φ	is the actual gas content by volume;
ΔP_{dif}	is the pressure drop in gas–liquid flow, N/m^2;
ΔP_{li}	is the pressure drop for the flow of the liquid, N/m^2;
G_{li} and G_g	are the discharges of liquid and gas, kg/sec;
β	is the discharge gas content by volume;
σ	is the surface tension of the liquid;
μ_{li} and μ_g	are the dynamic viscosities of liquid and gas, N·sec/m^2;
$Re_{li} = 4G_{li}/\pi d \gamma_{li}/V_{li}$	is the Reynolds number;
$Fr = 16G_{li}^2/\pi^2 g \gamma_{li}^2 d^3$	is the Froude number.

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