EFFECT OF THE VISCOSITY OF THE LIQUID PHASE ON THE TRUE GAS CONTENT AND THE REGION OF STRATIFIED FLOW OF A TWO-PHASE MIXTURE IN SLIGHTLY INCLINED PIPES

A. A. Tochigin, N. N. Elin, and V. G. Arsenov

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The experimental results obtained point to the noticeable effect of the liquid phase viscosity on the actual gas content and the existence of the laminated structure of the two-phase flow in the slightly inclined tubes. The Froude number for the nonramming liquid flow velocity is used to correlate the experimental data on different viscosities.

Different flow structures (forms) are seen in the motion of gas—liquid mixtures in pipes, the most characteristic forms being stratified, piston, and annular [1]. Since the main hydrodynamic characteristics depend on the form of the flow, the ability to correctly determine the region of existence of each type of flow structure is a necessary condition for the hydraulic calculation of a two-phase flow.

An important issue is study of the transition from piston to stratified flow, since this transition is accompanied by a very great change in the basic hydraulic characteristics of the flow (true gas content, resistance coefficient and, thus, pressure losses).

Several investigations [2-6] have studied the transition of the piston flow of a two-phase mixture to stratified flow. The experiments in [2] were conducted within a broad range of mixture velocities (Froude numbers), discharge gas contents, and inclinations of the pipe to the horizontal. The authors also proposed a method of generalizing test data pertaining to different flow conditions. However, it should be noted that the range of the physical properties of the components of mixtures investigated (mainly air—water mixtures) was fairly narrow. Thus, there is a need for further study of the laws of flow of a stratified flow within a broad range of physical properties of the components of the mixture.

The present work studies the effect of the viscosity of the liquid phase on the region of existence of stratified flow and the gas content of the flow.

The experimental studies were conducted with the motion of a gas—liquid mixture in a glass tube with an inside diameter of 13 mm and a length of 6.7 m. The liquid component of the mixture was water ($\mu = 1 \cdot 10^{-3}$ N·sec/m²), diesel fuel ($\mu = 3.6 \cdot 10^{-3}$ N·sec/m²), "Veretennoe AU" oil ($\mu = 41.9 \cdot 10^{-3}$ N·sec/m²), and solutions of this oil in the diesel fuel at two concentrations ($\mu = 21.1 \cdot 10^{-3}$ and $10 \cdot 10^{-3}$ N·sec/m²). Measurements were conducted for each value of viscosity in horizontal and descending flows, with inclinations of the tube at angles of 2°30', 6°30', and 8° relative to the horizontal. The Froude number of the mixture ($Fr_m = U_m^2/gd$) ranged from 0.4 to 16 for each inclination, while the discharge gas content ranged from 0 to 1 for each value of Fr_m.

The true volumetric gas content was determined by the method of cutting the tube off from the main. The experimental error was evaluated by the method described in [2] and was 6%. Figure 1 shows typical empirical dependences of the true gas content on the discharge gas content and the Froude number.

An increase in the viscosity of the liquid phase leads to a decrease in the true gas content. Figure 1a-c shows data obtained with different liquid viscosities. The inclination of the tube to the horizontal in these tests remained constant and was 6°30'.

Figure 1d-f shows results of measurements with a liquid viscosity of $10 \cdot 10^{-3}$ N·sec/m² and different angles of inclination of the tube to the horizontal. Analysis of the relations ob-

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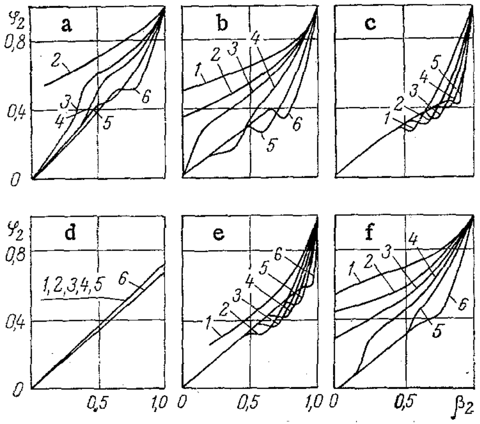

Fig. 1

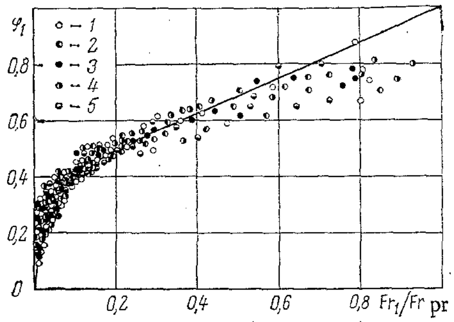

Fig. 2

Fig. 1. Dependence of the true gas content on the discharge gas content and the Froude number: $\alpha = 6°30'$: a) $\mu = 1\cdot10^{-3}$ N·sec/m^2; b) $10\cdot10^{-3}$; c) $41.9\cdot10^{-3}$; $\mu = 10\cdot10^{-3}$ N·sec/m^2; d) $\alpha = 0°$; e) 2°30'; f) 8°; 1) $Fr_m = 0.4$; 2) 1; 3) 2; 4) 4; 5) 8; 6) 16.

Fig. 2. Generalization of experimental data on true gas contents in a stratified flow of a two-phase mixture: 1) $\mu = 1\cdot10^{-3}$ N·sec/m^2; 2) $3.6\cdot10^{-3}$; 3) $10\cdot10^{-3}$; 4) $21.1\cdot10^{-3}$; 5) $41.9\cdot10^{-3}$.

tained shows that an increase in the angle of inclination of the tube leads to an increase in the true gas content when the structure of the flow of the mixture is stratified.

The results obtained are fully consistent with known laws. As is known, an increase in viscosity and a decrease in tube inclination lead to a decrease in liquid velocity. Here, the percentage of the tube cross section occupied by the gas phase (the true gas content) decreases.

To construct theoretical relations suitable for use within a broad range of discharge and physical parameters of the flow, it is necessary to have a reliable method of generalizing a large amount of empirical data. In [2], the results of measurements of true gas content with a stratified flow of an air—water mixture were represented in the coordinates φ_1 and $Fr_1 = \beta_1^2 Fr_m$. Such an approach makes it possible to obtain a single relation for a fixed tube inclination.

The effect of the tube inclination is accounted for by using the Froude number corresponding to the limiting value of the velocity of the mixture at which stratified flow is seen throughout the entire zone of existence of the two-phase flow ($0 \leqslant \beta_2 \leqslant 1$) [2]:

$$Fr_{pr} = \frac{2\sin\alpha}{\lambda}.$$

The family of curves in Fig. 1, when analyzed in the coordinates φ_1 and $\chi = Fr_1/Fr_{pr}$ gives a single relation for all viscosities of the liquid phase (Fig. 2). Analysis of the results obtained shows that the empirical relation [2]

$$\varphi_2 = 1 - \chi^{0.4} \text{ at } 0 \leqslant \chi \leqslant 0.18;\ \varphi_2 = 0.615(1-\chi) \text{ at } 0.18 < \chi \leqslant 1 \tag{1}$$

well describes the results of experiments in the region of moderate values of χ. At $\chi \gtrsim 0.35$, the empirical points are located somewhat below the theoretical curve (1).

The transition from stratified flow to piston flow was determined from the change in the form of the dependence of true gas content on discharge gas content. It was also visually determined. Throughout the region of piston flow, there is the linear relation $\varphi_2 = \varphi_2(\beta_2;\ Fr_m)$.

The transition to stratified flow is accompanied by a sharp change in the true gas content. The shift in flow structure does not occur at once, but rather within a range of values of β_2. The results of measurements in this transitional zone are characterized by poor reproducibility, which is due to the considerable lengths of the gas—liquid plugs — comparable to the distance between cutoffs.

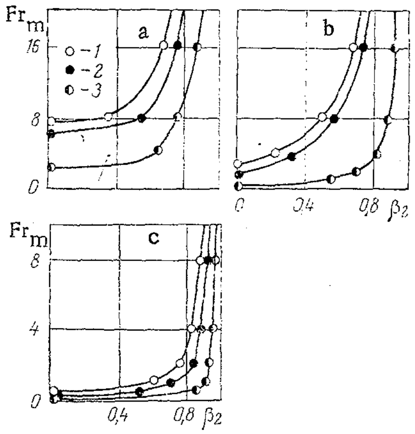

Fig. 3

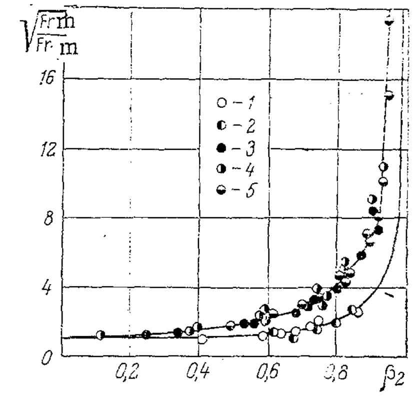

Fig. 4

Fig. 3. Position of the boundary of the transition from piston flow of a two-phase mixture to stratified flow: 1) $\alpha = 2°30'$; 2) $6°30'$; 3) $8°$; a) $\mu = 1 \cdot 10^{-3}$ N·cm/m² b) $10 \cdot 10^{-3}$; c) $41.9 \cdot 10^{-3}$.

Fig. 4. Generalization of experimental data on the position of the boundary of the transition from piston flow of a two-phase mixture to stratified flow: 1) $\mu = 1 \cdot 10^{-3}$ N·sec/m²; 2) $3.6 \cdot 10^{-3}$; 3) $10 \cdot 10^{-3}$; 4) $21.1 \cdot 10^{-3}$; 5) $41.9 \cdot 10^{-3}$.

Figure 3 presents certain test results in the coordinates Fr_m and β_2, these being the principal governing parameters for piston and stratified flows [2]. For all liquid viscosities, an increase in tube inclination leads to expansion of the zone of stratified flow into the region of lower discharge gas contents. An increase in liquid viscosity expands the zone of piston flow.

As might be expected, tube inclination and viscosity exert the greatest effect at moderate Froude numbers, which corresponds to moderate mixture velocities. The effect of gravitational and viscous forces is quite substantial at such velocities. The parameter Fr_m/Fr_0, where $Fr_0 = 0.2 + Fr_{pr}$, was proposed in [2] to generalize test data on the transition from piston to stratified flow in the motion of air–water mixtures in horizontal and slightly inclined pipes. Such an approach has made it possible to generalize results pertaining to different pipe inclinations. The use of the parameter Fr_m/Fr_0 is inconvenient in that it takes different values at the boundary of the transition in the case $\beta_2 = 0$, while the ratio Fr_m/Fr_{pr} is identically equal to unity. The term 0.2 introduced into the expression for Fr_0 does not have a clear physical significance, first of all, and, secondly, it may be different for pipes of different diameter and roughness. The use of the quantity Fr_m/Fr_{pr} as the generalizing parameter is physically more valid. Figure 4 shows the results of the experiment represented in the coordinates $\sqrt{Fr_m/Fr_{pr}}$ and β_2.

Analysis of these relations shows that the data obtained in the mixtures with high liquid-phase viscosities is grouped along a single curve. At the same time, the test points corresponding to the air–water flow and the flow of the mixture of air and diesel fuel are located below this curve. The reason for such stratification is that the no-head flow of water and diesel fuel was turbulent for all inclinations of the tube, while the flow of the other liquids was laminar.

Based on the above, we deem it necessary to use the following two equations to determine the boundary of the transition from piston to stratified flow of the mixture:

$$
\begin{aligned}
Fr^* &= Fr_{pr} \exp(-0.5\beta_2)\,\beta_1^{-2} \quad \text{at} \quad Re \leqslant 2320, \\
Fr^* &= Fr_{pr} \exp(-2.5\beta_2)\,\beta_1^{-2} \quad \text{at} \quad Re > 2320,
\end{aligned}
\tag{2}
$$

where Re is the Reynolds number, calculated for the velocity of no-head flow of the liquid. At $Fr_m \geqslant Fr^*$, the flow regime is piston. At $Fr_m < Fr^*$, the flow is stratified.

NOTATION

U_m, velocity of the mixture, m/sec; d, inside diameter of the tube, m; α, angle of inclination of the tube to the horizontal, degrees; g, acceleration due to gravity, m/sec^2; μ, absolute viscosity, N·sec/m^2; β_2, discharge gas content; $\beta_1 = 1 - \beta_2$, discharge liquid content; φ_2, true volumetric gas content; $\varphi_1 = 1 - \varphi_2$, true volumetric liquid content; λ, resistance coefficient; Fr_m, Froude number of the mixture; Fr_1, Froude number calculated from the corrected liquid velocity; Fr_{pr}, Froude number calculated from the velocity of no-head flow of the liquid over the entire cross section of the given tube; Fr*, Froude number corresponding to the transition from piston to stratified flow; $\chi = Fr_1/Fr_{pr}$, parameter; Re, Reynolds number.

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INTENSIFICATION OF HEAT EXCHANGE IN TUBE BUNDLES IN A TRANSVERSE FLOW

V. K. Migai

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Data are presented from an experimental study of heat exchange involving reticular bundles of smooth and wavy tubes. A formula obtained for a modified Reynolds analogy generalizes published data for rough tubes and tubes with intensifiers.

Tube bundles located transversely to the flow are widely used in modern heat exchangers, and intensifying heat exchange in such bundles is an important problem. The relatively high level of turbulence caused by periodic disruptions of the flow make this problem very difficult to solve. The flow is two-dimensional in the case of flow over individual tubes in conventional staggered and corridor bundles, and turbulence is generated as a result of the nonuniformity of the velocity field in planes normal to the tube axis. If we create an additional nonuniformity in the direction of the tube axis, heat exchange is additionally intensified due to an increase in the turbulence level. Such additional nonuniformity is seen with the use of reticular bundles, i.e., bundles with a latticelike arrangement of the tubes. There has not been sufficient study of such bundles [1], and below we present the results of a study conducted on an experimental air unit of one type of reticular corridor bundle composed of straight and wavy tubes. It should be noted that, on the whole, there has not yet been any study of reticular bundles of wavy tubes.

The bundle (Fig. 1) was composed of tubes with an outside diameter d = 15 × 1 and served as the heating surface of a two-pass (air and gas) air heater. The spacings of the tubes across the bundle width $S_1 = 22$ mm, $S_1/d = 1.47$. The spacings through the depth (two intervals) $S_2' = 17$ mm, $S_2'' = 44$ mm, $\bar{S}_2 = 30.5$ mm, $\bar{S}_2/d = 2.03$. The presence of two intervals depthwise was decided upon the basis of considerations related to the design of the heat exchanger. Cold air was heated by air (gas) heated in an electric heater. The temperature of the air and gas was determined by averaging the readings of eight thermocouples installed in each case

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