EFFECT OF SURFACTANTS ON THE FLOW FRICTION AND FLOW STRUCTURE OF A GAS-LIQUID DISPERSION IN A VERTICAL ANNULAR CHANNEL

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The authors report on the effect of adding a surfactant on two-phase flow structure, flow friction, and true gas content in an annular channel.

There have been numerous studies of gas-liquid dispersions flowing in channels of various shapes. It is sufficient to recall the work of Levich [6], Teletov [9], Miropol'skii and Styrikovich [7], Kutateladze [1], and Kosterin et al. [2, 3].
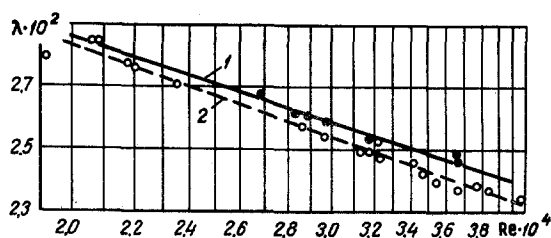

Fig. 1. Flow friction of a smooth annular channel for a 0.1% solution of "Progress" in water: 1) turbulent flow of water, 2) turbulent flow of solution.

However, there has been relatively little investigation of the hydrodynamics of gas-liquid flows in the annular channel formed by concentric tubes. Even less attention has been paid to the flow processes of gas-liquid dispersions in annular channels in the presence of surfactants (SA) and frothing. At the same time, in practice it is comparatively rare to encounter a liquid with a clean surface. Usually the latter is more or less covered with SA which, when the liquid flows, may cause stable frothing, an important factor in a number of technical processes (steam generation, flotation, fire-extinguishing, etc.) and when SA are used in the oil industry.

This paper describes the results of an experimental investigation of the effect of the surfactant "Progress" on the true gas content, flow structure, and flow friction of an air-water dispersion flowing upwards through a smooth vertical annular channel in the range of variation of φ from 0.00 to 0.5 at a mean pressure in the channel of 1.2 kg/cm^2, $\mathrm{Re}_C = 10^4$, $\mathrm{Fr}_C = 5\text{–}20$ and $\mathrm{We} = 184\text{–}330$.

The Weber number was varied by adding "Progress" to the water in amounts ranging from 0.05 to 0.7% by weight. The surface tension of the solution (as compared with that of pure water) was reduced by a factor of up to 2.7.

"Progress" is obtained by sulfonating a mixture of olefins $C_8\text{–}C_{18}$ with sulfuric acid monohydrate with subsequent neutralization of the mixture of sulfo esters with caustic soda.

"Progress" has the structural formula

$$\begin{matrix} R \\ R \end{matrix}\!\!\!>\!\!CHOSO_3Na \; .$$

The principal technical characteristics of this substance are given in specifications VTU no. 3152–58.

In the amount of 0.7% by weight "Progress" has almost no effect on the viscosity of water, which excludes the possibility of a change in the viscosity of the liquid affecting the hydraulic losses. The viscosity of the water was measured with an Ostwald-Pinkevich viscometer.

In the experimental apparatus the annular gap was formed by an inner metal cylinder and an outer cylinder of transparent acrylic plastic. The outside diameter of the inner cylinder was 88 mm, the inside diameter of the outer cylinder 116 mm. The total length of the channel including the inlet section was 1250 mm.

In order to facilitate a visual investigation, the inner cylinder was coated with black lacquer, while the outer cylinder was carefully polished. The relative roughness of the surfaces of the annular working channel was r/k = 10 000–12 000.

The liquid was circulated by a centrifugal pump with a capacity of 3 l/sec. A uniform supply of water to the annular channel was ensured by using a constant-level tank. At the inlet to the working section we introduced a mixer and a ring consisting of a brass tube with twelve nozzles through which air entered the liquid. This system ensured a uniform supply of air over the entire perimeter of the annular channel.

Holes for static pressure tubes were made in the outer cylinder at intervals of 100 mm.

The static pressure distribution over the length of the channel was measured with an inclined multitube manometer, the water flow rate was determined gravimetrically, and the air flow rate with a double orifice; the water temperature at the inlet and outlet of the working section was checked with mercury thermometers. The surface tension was measured with a stalagmanometer, with an electronic device for automatically counting the drops, developed at the Institute of Physical Chemistry AS USSR. In each experiment the measurements were repeated not less than 3 times and then averaged. In studying two-phase flows the determination of static pressure is particularly troublesome owing to the large pressure pulsations, whose amplitude sometimes exceeds the static pressure drop. In order to avoid this, we used special compensating vessels made of transparent plastic for

visual observation of the degassing of the liquid entering the manometer and connecting coils with a very small inside diameter. All this ensured a high level of inertia of the static pressure sampling system and made it possible to measure the friction losses with sufficient accuracy.

The true volumetric gas content was determined by irradiating the working channel with β-rays instead of the harder γ-rays used in [7, 8]. This method makes it possible to determine the mean value of the true gas content at any point of the working section. For this purpose we specially designed a device using thallium 204 as the radioactive isotope. The entire plane of the channel cross section was irradiated at a point on the hydrodynamically stabilized part of the channel.

Before proceeding to investigate the effect of SA on the flow friction and true gas content, we determined the hydraulic characteristics of the annular channel in relation to a single-phase liquid (water) flow at $\text{Re} = 10^4 - 4 \cdot 10^4$. Apart from the main test stand, for these preliminary measurements we used a horizontal apparatus with an annular channel 2.5 m long in which the outside diameter of the inner tube $d_1 = 24$ mm and the inside diameter of the outer tube $d_2 = 35.6$ mm. On this apparatus the static pressure drop reached 2.5 m H_2O.

Experiments on a horizontal apparatus had to be carried out for the following reasons.

It is known that SA added to water moving through channels is adsorbed on the very fine air bubbles that are trapped by the liquid flow in the presence of SA. Thus, there is formed a two-phase system with a microdisperse structure, which can be detected by examining the liquid under the microscope at small magnifications.
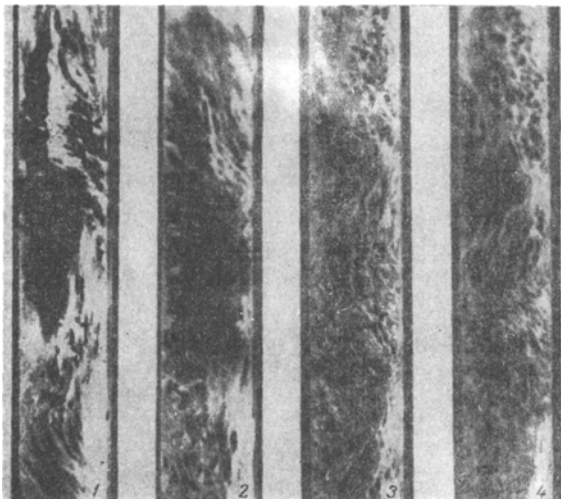

Fig. 2. Flow structure of gas-liquid dispersion in an annular channel ($\text{Re}_c = 10^4$, $\varphi = 0.4$): 1, 2) slug flow without SA, $\text{We} = 184$; 3, 4) dispersed flow with frothing following the introduction of SA, $\text{We} = 264$.

Consequently, when this kind of liquid flows through a vertical channel it is necessary to take into account the presence of a gas phase in the flow. However, in

our experiments the gas phase was present in very small volumes of about 2%, and therefore the β-irradiation method employed did not give quantitative results. When the channel is arranged horizontally, it is no longer necessary to determine the true weight of the column of gas-liquid dispersion and any related errors are eliminated.
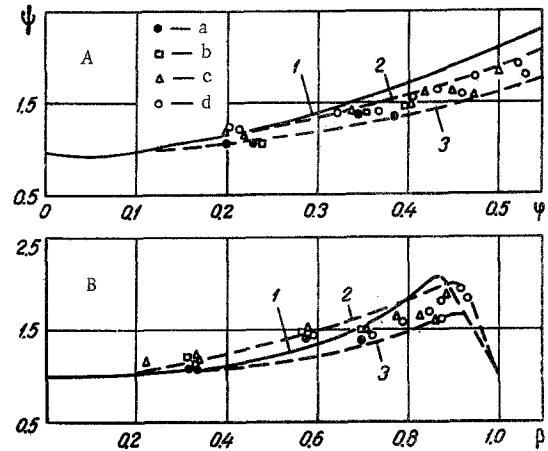

Fig. 3. Effect of "Progress" on the relation between the reduced resistance coefficient and (A) the true volumetric gas content and (B) the flow-rate volumetric gas content: 1) experimental data for an air-water dispersion without SA, $\sigma = 74.0$ dyne/cm; 2 and 3) experimental data for a gas-liquid dispersion with SA, σ from 27.8 to 74.0 dyne/cm (a) 27.8; b) 30.2; c) 41.7; d) 52.4).

In analyzing the results we determined the value of λ for pure water and water containing 0.1% SA from the Darcy-Weisbach formula

$$\Delta P = \lambda \, \frac{L}{2\,(r_2 - r_1)} \, \frac{v_1^2}{2g} \, \gamma_1 \qquad (1)$$

and constructed a graph of resistance coefficient vs. Reynolds number (Fig. 1).

It was established that adding SA to the flow of water reduced the flow friction (line 2) as compared with the resistance of the channel to water alone (line 1).

A similar effect was previously noted in [10-15], whose authors point out that long chainlike SA molecules in the boundary layer improve the slippage conditions, which reduces the shear stresses at the tube walls.

The subsequent experiments were made on a vertical annular channel carrying an air-water dispersion with and without "Progress" at true volumetric gas contents φ from 0.0 to 0.5.

In the experiments we kept the parameters Re_c, $\bar{\mu}$, Fr_c, $\bar{\gamma}$ constant and varied the surface tension σ and the flow-rate gas content β.

In the measuring section of the vertical experimental apparatus we created a steady flow regime with given values of v_c and φ for a flow of dispersion without SA. The desired values of v_c and φ were selected by regulating the flow rates of water and air. The

pressure drops ΔP on the measuring section L were recorded, and the flow structure was photographed with a motion-picture camera. We then added "Progress" to the water in a given concentration by weight, repeated the measurements of φ and ΔP_σ, and recorded the flow structure.
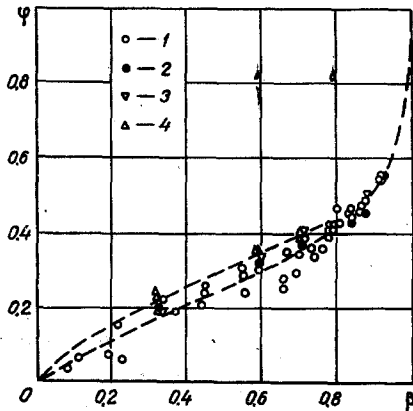

Fig. 4. True gas content as a function of flow-rate gas content for a vertical annular channel: 1) for gas-liquid dispersion ($\sigma = 74.0$ dyne/cm); 2, 3, 4) for a gas-liquid dispersion with "Progress" (σ respectively 52.4, 41.7, and 27.3–30.2 dyne/cm).

Parts 1 and 2 of Fig. 2 relate to slug flow with $\varphi = 0.42$ without SA; when SA is added in the amount of 0.05% by weight of water the flow structure changes radically, becoming more dispersed (Figs. 2, 3, and 4). When the concentration of SA is further increased by a factor of 10–12, the structure of the gas-liquid flow is only slightly affected.

When SA is introduced into a gas-liquid mixture the free surface energy of the liquid-gas system is reduced, as a result of which the strength of the surface films of the air bubbles declines [6]. Clearly, therefore, in our experiments when "Progress" was added to the flow, large air bubbles were broken down into smaller ones under the action of turbulent fluctuations with a constant characteristic.

Thus, for an examination of the flow structure we see that when even a small quantity of SA (0.05%) is added to the flow the dispersity increases as a result of the breakdown of large bubbles at constant β. Therefore the true gas content of the mixture also increases, while the relative phase velocities fall, which, as Krylov [4] has shown, leads to a decrease in flow friction. This confirms the results of our experiments analyzed by Teletov's method.

Teletov [9] was the first to formulate the general differential equations of hydrodynamics of two-phase mixtures, on the basis of which he derived dimensionless similarity criteria for such flows, also proposing a well-founded criterial method of analyzing the experimental data in the form

$$\frac{\lambda_c}{\lambda(\text{Re}_c)} = \psi(\beta, \text{Fr}_c, \text{We}, \bar{\mu}, \bar{\gamma}, \dots \text{ etc.}), \quad (2)$$

$$\lambda_c = \frac{2\Delta P}{\gamma_p L} \bigg/ \text{Fr}_c \left[\eta \frac{\beta}{\varphi} + (1-\eta)\frac{1-\beta}{1-\varphi} \right]. \quad (3)$$

On the basis of this work we may assume that under the conditions of our experiments the investigated quantities φ and λ_c are functions of β and We.

The results of these experiments are presented in Fig. 3, A and B.

It is clear from Fig. 3A that the ratio

$$\psi = \lambda_c/\lambda(\text{Re}_c)$$

increases monotonically with increase in the true gas content in the range from 0 to 0.55 and falls by 10–20% when "Progress" is introduced. In the range of variation of β from 0 to 0.9 (Fig. 3B) the values of Ψ lie approximately in the same region both in the pure gas-liquid flow (curve 1) and in the flow to which "Progress" has been added (curves 2, 3).

Upon examining the φ vs. β curves for flows with and without AS (Fig. 4), we see that when "Progress" is introduced, a larger true gas content φ corresponds to the same flow-rate gas content β, which, in accordance with Eq. (3), leads to a decrease of λ_c by about 10–15%.

Lutoshkin [5] came to a similar conclusion when investigating the effect of SA on the operation of air lifts.

Thus, the results of our study of flow structure and our analysis of the measurements are in qualitative agreement. It should be noted that when SA is added, the static pressure fluctuations in the flow are reduced by a factor of 2–3.

NOTATION

$\text{Re}_c = (1-\varphi)2v_1(r_2 - r_1)/\nu_1 - 2\varphi v_2(r_2 - r_1)/\nu_2$ is the Reynolds number of dispersion flow; ν_1 and ν_2 are the kinematic viscosities of water and air; r_1 and r_2 are the radii of inner and outer cylinders; $v_1 = (G_1/\gamma_1)F(1-\varphi)$, $v_2 = (G_2/\gamma_2)F\varphi$, and $v_c = v_1 + \varphi(v_2 + v_1)$ are the mean flow velocities of water, air, and dispersion; $\text{Fr}_c = (v_c^2/2g)(r_2 - r_1)$ is the Froude number of dispersion flow; $\text{We} = (2v_c^2)(r_2 - r_1)/\sigma g$ is the Weber number; β is the flow-rate volumetric gas content, equal to ratio of gas volume flow rate to dispersion volume flow rate; φ is the true volumetric gas content; G_1 and G_2 are the mass flow rates of water and air; $\eta = \gamma_2\beta/\gamma_p$ is the mass flow-rate gas content; γ_1 and γ_2 are the specific weights of water and air; $\gamma_p = \gamma_1 - \beta(\gamma_1 - \gamma_2)$ is the flow-rate specific weight of dispersion; $\lambda(\text{Re}_c)$ is the resistance coefficient for single-phase flow of one of the phases of the dispersion at a Reynolds number equal to the Reynolds number of the dispersion; λ_c is the hydraulic resistance to flow of disperse system; ψ is the reduced resistance (deviation of λ_c from $\lambda(\text{Re}_c)$); $\bar{\mu}$ is the viscosity ratio of the phases; $\bar{\gamma}$ is the specific weight ratio of the phases; σ is the surface tension.

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