WAVE PROCESSES IN A GAS – LIQUID STREAM

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Experimental data are presented on the wave characteristics of the interphase boundary in separated gas–liquid wave flow. An estimate is given of the influence of the waves on the magnitude of the head loss by the friction of the gas–liquid mixture in a horizontal tube.

It has been established in measurements of the velocity profile in a separated gas–liquid stream [1] that waviness on the interphase boundary exerts a noticeable influence on both the velocity distribution in both phases and on the magnitude of the head loss. A rheostat transducer whose operating principle is based on the change in the resistivity of an electrical loop during oscillations of the interphase boundary has been fabricated to measure the wave characteristics (the wave amplitude and period). The transducer consists of a polyfluoroethylene resin core on which a high-resistivity wire is wound in one series after which the outer surface of the transducer is coated with a waterproof lacquer. A 1 mm wide slot was made along the whole core to the metal of the high-resistance wire. Placed in parallel to the slot at a spacing of several millimeters was a bare electrode which was joined to the interphase boundary itself with turns of the high resistance wire, for which the transducer was placed in an experimental tube with a gas–liquid stream so that the core axis was perpendicular to the tube axis. Depending on the liquid depth at the point where the transducer was placed, the electrical resistivity of the high-resistance winding changed and a signal was recorded on photographic paper of an N-700 loop oscillograph. A transducer of such construction has no inertia, which allows recording of waves with sufficiently high frequency. A typical oscillogram and photograph of the wave process on the interphase boundary are presented in Fig. 1. The normalized correlation function of the process is a damped cosine and is approximated [2] by:

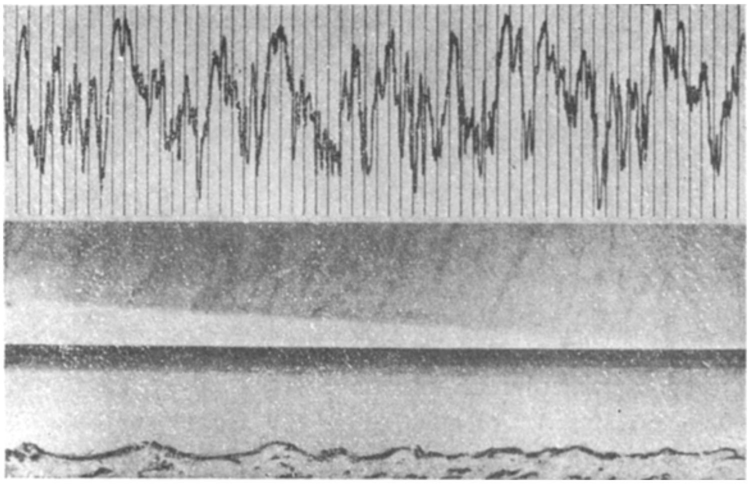

Fig. 1. Oscillogram of the oscillations of the interphase boundary in a gas–liquid stream. $\overline{\varphi}_2 = 0.8$; $Re_2 = 15 \cdot 10^3$, $Re_1 = 50 \cdot 10^3$. Photograph of an interphase boundary $\overline{\varphi}_2 = 0.9$; $Re_2 = 15 \cdot 10^3$; $Re_1 = 65 \cdot 10^3$.

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$$R(\tau) = D_0 e^{-\alpha_1 \tau} \cos(\beta_1 \tau). \quad (1)$$

Here α_1 and β_1 are constants of the process.

The damping of the correlation function (1) indicates the ergodicity of the waviness process on the interphase boundary in a gas–liquid stream.

Applying a Fourier cosine transformation to (1), we obtain the energy spectrum of the waviness in the following form [3]:

$$S = \frac{D_0 \rho_1}{2\pi} \left[\frac{\alpha_1}{\alpha_1^2 + (\omega + \beta_1)^2} + \frac{\alpha_1}{\alpha_1^2 + (\omega - \beta_1)^2} \right]. \quad (2)$$

Determining the magnitude of the variance from the experimental curves recording the waviness, and the constants α_1 and β_1 of the process from the correlation function (Fig. 2), the unnormalized energy spectra of the waviness (Fig. 2) were computed from (2). As the velocity of the mixture motion increases, the waviness intensity grows and the spectrum narrows. For a mixture motion mode close to stoppage, all the waviness energy is concentrated in a narrow frequency band (curve 3 in Fig. 2). A negligible rise in the velocity of the mixture motion will hence result in a jump passage of the stream to a new (stoppage) flow which is characterized by the successive motion of liquid and gas stoppers.

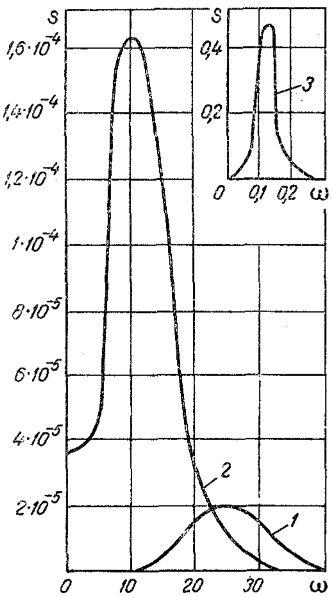

Fig. 2. Unnormalized energy spectra of waviness on the interphase boundary $\bar{\varphi}_2 = 0.9$ (S, kg·s/m^2; ω, sec^{-1}): 1) Re_2 = 28,000; 2) 36,000; 3) 85,000.

A rise in the velocity of mixture motion also results in displacement of the maximum point of the spectrum towards the lower frequencies. The shift of the maximum point of the waviness spectrum is shown in Fig. 3 for $\bar{\varphi}_2 = 0.9$.

It is shown in [4, 5] that the maximum of the turbulent energy spectrum of the gas phase in the layer of atmosphere near the water and the maximum of the waviness energy spectrum practically coincide, i.e., a gas layer near the water and the wave surface of a liquid phase oscillate in resonance. This latter fact is important to the comprehension of the physics of a gas–liquid mixture flow because the wave height on the interphase boundary is capable of reaching the size of the tube diameter (whereupon the passage from the separated flow mode to the stoppage mode occurs), and therefore resonance phenomena take over both phases entirely in the stoppage mode.

The influence of the wave characteristics on the magnitude of the head loss was estimated as follows. Formulas to compute the loss of head by friction in the case of a plane interphase boundary were proposed in [6] for a separated mixture flow configuration. A comparison between these formulas and test results showed that the measured pressure drop for a wavy interphase boundary is always 20% greater than the theoretical on the average. For a plane interphase boundary the error in the theoretical formulas as compared to test results is ±5%. As the waviness increases on the interphase boundary, the deviation of the test results from the theoretical increases. Starting therefrom, it can be considered that the loss of

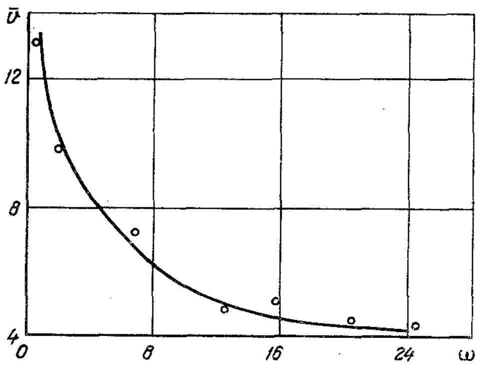

Fig. 3. Shift of the maximum point of the waviness energy spectrum in a gas–liquid stream as a function of the mean gas phase velocity $\bar{\varphi}_2 = 0.9$ ($\bar{v}$, m/sec, ω, sec^{-1}).

head by friction in a developed wavy flow mode of a gas–liquid mixture is approximately 20% greater, compared to those cases when the interphase boundary were plane.

It is customary to understand a wavy gas–liquid stream to be such for which the wave height is less than or at least of the same order of magnitude as the tube diameter. Investigations conducted permitted refinement of the boundary of wave stream existence. Plug (shell) flow at $Fr \leq 10$ is also a wave flow. This is explained as follows. For low Froude numbers ($Fr \leq 10$) the fluid phases move as solid cylinders in the tube, filling the whole tube section entirely. Visually this is seen as the gas and liquid plugs move at the same velocity, i.e., $\overline{\varphi}_2 = \beta$, however, an instrumental determination of the true gas content for the given modes shows [6] that $\overline{\varphi}_2 < \beta$, i.e., there is a relative phase velocity. We easily explain such a paradox if it is considered that the liquid plugs are waves whose shape moves with the phase velocity c hence entraining the gas within the troughs of the waves, i.e., between the liquid plugs. It hence follows that the velocity of the gas phase $\overline{v}_2$ should equal the phase velocity c:

$$c = \overline{v}_2 \quad \left(\overline{v}_2 = \frac{Q_2}{\overline{\varphi}_2 F}\right). \tag{3}$$

Indeed, by measuring the repetition rate of the liquid plugs by using the transducer described above, and the wavelength (the length of the liquid and gas plugs) visually, we obtain (for $Fr \leq 10$)

$$c = \overline{v}_2. \tag{4}$$

As the Froude number increases, the dependence (4) is spoiled since a leakage of the gas phase occurs between the tube walls and the liquid plugs.

Considering the plug mode as some limiting wavy mode, the onset of the self-similar function $\overline{\varphi}_2 = \overline{\varphi}_2(Fr, \beta)$ [6], which holds for the number $Fr \geq 4$ (for a horizontal tube) can be explained graphically. The self-similarity of the function $\overline{\varphi}_2 = \overline{\varphi}_2(Fr, \beta)$ means that for $Fr \geq 4$ gravity ceases to act, i.e., the acceleration of gravity is equilibrated by the centripetal acceleration; self-similarity of the function $\overline{\varphi}_2 = \overline{\varphi}_2(Fr, \beta)$ holds upon compliance with the relationship

$$g = \omega^2 R_1, \tag{5}$$

where $R_1 = \lambda/2\pi$; λ is the wavelength (the length of the liquid and gas plug), ω is the repetition rate of the liquid and gas plugs.

An experimental verification of the dependence (5) showed that $g \approx \omega^2 R_1$ for $Fr = 4$ and $g < \omega^2 R_1$ for $Fr > 4$.

The plug repetition rate is connected with the true velocity of the liquid phase by means of the relationship

$$Sh = \frac{\omega d}{\overline{u}_1}. \tag{6}$$

It has been established experimentally that the Strouhal criterion in the zone of self-similarity of the function $\overline{\varphi}_2 = \overline{\varphi}_2(Fr, \beta)$ is a constant analogous to the constant value of the Strouhal number in a single-phase stream in the zone of developed turbulence [7]. This fact shows that for sufficiently high Froude numbers the gas–liquid flow parameters are self-similar, i.e., are independent of the Froude criterion just as its parameters in single-phase streams are, for sufficiently high Reynolds number, independent of this criterion.

NOTATION

ω	is the angular wave frequency, repetition rate of the liquid and gas plugs;
$\overline{u}_{1(2)} = \overline{w}/\overline{\varphi}_{1(2)}$	is the true velocity of the liquid and gas phases;
$\overline{w} = (Q_1 + Q_2)/F$	is the reduced mixture velocity;
$Q_{1(2)}$	is the liquid and gas phase discharge;
F	is the cross-sectional area of the tube;
$\overline{\varphi}_{1(2)} = F_{1(2)}/F$	is the true gas content;
$\beta = Q_2/(Q_2 + Q_1)$	is the discharge gas-content;
$F_{1(2)}$	is the cross-sectional area of the tube occupied by the liquid–gas phase;
d	is the tube diameter;

$Fr = \bar{w}_2/gd$	is the Froude criterion;
g	is the acceleration of gravity;
Sh	is the Strouhal criterion;
ρ_1	is the liquid density;
D_0	is the variance (root-mean-square deviation of coordinates of an interphase boundary point from the mean position).

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