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WAVE CHARACTERISTICS OF FALLING FILM FLOWS IN A CO-CURRENT GAS FLOW

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Data is presented from measurements of the frequencies, lengths, amplitudes, and phase velocities of waves in a falling annular flow of water and air in a pipe.

Film-type heat- and mass-transfer apparatus have come into wide use in different sectors of industry. The rate of production processes in such apparatus is determined to a large extent by the condition of the phase boundary. Studies of the structures of waves on the film surface [1-5] have shown that there are two classes of waves: large waves, which transport most of the liquid, and small waves, which overlay a thin layer of liquid (ripples). The wave parameters of two-phase film flows was studied in [1-5, 6, 7]. These studies pertain mainly to two-phase annular flows with thin films of liquids ($Re_q < 4000$) and high gas velocities ($v_g > 20$ m/sec), i.e., for flows in which drop removal from the surface of the liquid film is seen [2].

Presented below are results of experimental studies of the wave characteristics of liquid films flowing in a 30-mm-diameter pipe in a co-current gas flow. The flow-rate characteristics of the films were varied within the range $3500 < Re_q < 20{,}000$, while those of the gas were varied within the range $8000 < Re_g < 41{,}000$. The local characteristics of the film flow were measured by electrical methods [8, 9] and recorded in the form of oscillograms by recording devices. The length of the test section was 2400 mm. The measurements were made at five points of the test section. The length of travel of the film to the measurement points was 250, 500, 750, 1000, and 1625 mm. The velocity of the waves and the profile of the film surface were found from the known distance between the transducers and the time of passage of the waves over this distance. The experimental unit, measurement methodology, and method of analysis of the test data were detailed in [9].

The measurements showed that, as in [1, 3], the wave parameters of the liquid film are of a statistical nature, and the law of distribution of these quantities is close to a normal law. The thickness of the film and the frequency, for prescribed flow-rate characteristics, nearly stabilize by the time the flow travels 750 mm into the pipe, while the amplitude increases somewhat with an increase in the length of film travel. The mean values of wave frequency on the stabilized section are shown in Fig. 1 as a function of the rate parameters of the flow. Here, the dimensionless frequency of the waves

$$f^* = f\sigma(\rho_q g \nu_q)^{-1}. \tag{1}$$

It is apparent from the figure that the wave frequency is affected in almost equal measure by the rates of flow of the liquid and gas, with the liquid flow rate having the opposite effect. The latter is due to the fact that an increase in liquid flow rate is accompanied by an in-

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crease in the mean thickness of the film [7], and larger waves are formed. It was established that the wave frequency may be almost twice as great on the initial section of the pipe (s = 250 mm) as on the stabilized section, which agrees qualitatively with [1, 2]. The relations depicted in Fig. 1 are approximated by the following equation:

$$f^* = \exp(4.85 + 0.25\cdot 10^{-4}\mathrm{Re}_2 - 0.375\cdot 10^{-4}\mathrm{Re}_q). \tag{2}$$

The dimensionless phase velocity of the waves was determined from the formula

$$c^* = c\sigma^{0.5}(\rho_q g \nu_q^2)^{-0.5} = \lambda f \sigma^{0.5}(\rho_q g \nu_q)^{-0.5}. \tag{3}$$

Figure 2a shows the relation for the dimensionless frequency of the waves with different Reynolds numbers for both phases. It is apparent from this figure that the phase velocity of the waves increases with an increase in the flow rate of the phases, although the effect of liquid flow rate on wave velocity is somewhat weaker than the effect of gas flow rate. This is due to the fact that the wave frequency decreases somewhat more rapidly than the wavelength increases when the Reynolds number of the liquid increases. The path of the wave velocity relations is similar to the path of the functions shown in [6]. The relations in Fig. 2a are described by the formula

$$c^* = \exp(8.35 + 0.375\cdot 10^{-4}\mathrm{Re}_q + 0.205\cdot 10^{-4}\mathrm{Re}_2). \tag{4}$$

Information on wavelength in the investigated range of flow rate characteristics is easily obtained on the basis of (3) and the data shown in Figs. 1 and 2a, since

$$\lambda^* = c^* f^{*-1} = \lambda(\rho_q g)^{0.5}\sigma^{-0.5}. \tag{5}$$

The amplitude of the waves was calculated as follows:

$$A = 0.5(\delta_{\mathbf{cr}} - \delta_t). \tag{6}$$

Analysis of the experimental data showed that the dimensions of the waves are affected by the rates of flow of both phases and the length of film travel. An increase in the velocity of the gas flow "smoothes" the relative roughness of the phase boundary. We obtained the following relation for the dimensionless amplitude

$$A^* = Ag^{1/3}\nu_q^{-2/3} = 0.5\delta^*[0.3 + \mathrm{Re}_q^{-0.1} - 0.278\cdot 10^{-4}\mathrm{Re}_g + (l/s)^{-0.615}]. \tag{7}$$

The data on wave amplitudes agrees qualitatively with the results in [5] and is of the same order of magnitude, although it differs quantitatively due to the different conditions under which the experiments were conducted. Values of the dimensionless film thickness δ^*, entering into (7), are shown in [7] for the experimental conditions used.

The basic characteristics of the wave flow can be related to each other through the characteristic Reynolds number

$$\mathrm{Re}_W = \lambda f A \nu_q^{-1}. \tag{8}$$

The dependences of the Reynolds wave number on the rate characteristics of the falling flow are shown in Fig. 2b. It is evident from the figure that Re_W increases with an increase in the liquid flow rate in the film and decreases with an increase in the velocity of the gas flow. It also follows from Fig. 2b that there is in essence a value of liquid flow rate (Re_q) which, if exceeded, results in degeneration of the dependence of the Reynolds wave number on liquid flow rate. The latter, obviously, can also take place if the liquid separates from the film surface. The dependences shown in Fig. 2b are approximated by the equation

$$\mathrm{Re}_W = \exp(0.3063 - 0.6287\cdot 10^{-4}\mathrm{Re}_g)\,\mathrm{Re}_q^{0.86}. \tag{9}$$

It turned out to be more convenient to correlate the pressure loss in two-phase annular flow with the Reynolds wave number of the film rather than with the shear stress on the phase boundary, as in [2]. Determination of this stress is difficult. Figure 3 shows the relation between pressure losses along the pipe and the Reynolds number Re_W. It is apparent from the figure that there is a direct relationship between the unit pressure losses and the value of the Reynolds wave number of the film. Despite the fact that an increase in the velocity of the gas flow (Re_g) is accompanied by a decrease in Re_W (Fig. 2b), the unit pressure drops in-

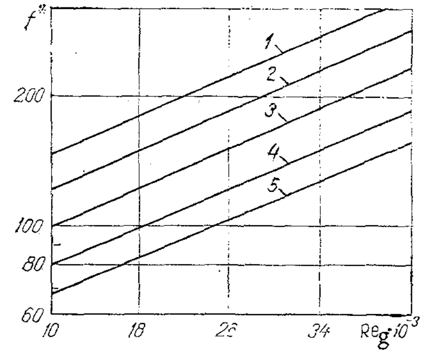

Fig. 1. Dependences of the dimensionless wave frequency on the Reynolds number of the gas: 1) $Re_q = 4 \cdot 10^3$; 2) $8 \cdot 10^3$; 3) $12 \cdot 10^3$; 4) $16 \cdot 10^3$; 5) $20 \cdot 10^3$.

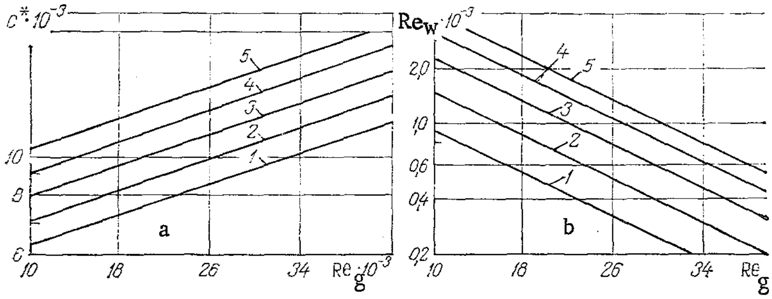

Fig. 2. Values of the dimensionless phase velocity of the waves (a) and the Reynolds wave number (b) (see Fig. 1 for notation).

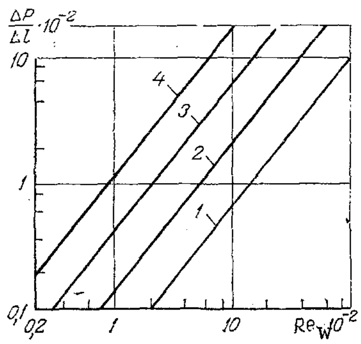

Fig. 3. Relation between pressure losses and values of Re_w: 1) $Re_g \cdot 10^4 = 1$; 2) 2; 3) 3; 4) 4.

crease, since their magnitude is proportional to the values of Re_g to the power 1.75 [10]. The relations in Fig. 3 are described by the formula

$$\frac{\Delta P}{\Delta l} = \exp(1.162 \cdot 10^{-4} Re_g - 5.388) Re_w^{1.2}. \tag{10}$$

Calculation of the resistances in two-phase annular flows by means of Eqs. (9) and (10) does indeed accurately reflect the physical essence of the phenomena under consideration, since it is the structure of the small waves that determines the roughness of the phase boundary and the amount of hydrodynamic resistance offered [4].

In conclusion, we should note that the relations obtained here are valid only for the indicated range of flow-rate parameters, for which there is almost no drop removal of liquid from the film surface.

NOTATION

f, frequency; σ, surface tension; ρ, density; g, acceleration of body forces; ν, kinematic viscosity; $c = \lambda f$, phase velocity of waves; λ, wavelength; δ_{cr}, δ_{tr}, film thickness at wave crests and troughs, respectively; $\delta^* = \delta g^{1/3}\nu_q^{-2/3}$, dimensionless thickness of film; δ, mean thickness of film; l, pipe length; s, length of film travel; $Re_q = 4v_q\delta\nu_q^{-1}$; $Re_g = v_g d\nu_g^{-1}$; v, velocity; d, pipe diameter. Indices: g, gas; q, liquid.

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