HYDRODYNAMICS OF DESCENDING TURBULENT FLOW OF LIQUID FILM AND GAS

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Experimental data is presented for the hydrodynamics of a descending annular flow of water and air for a separate flow mode with no separation and entrainment of drops.

The use of a single-pass film mode in heat and mass transfer equipment significantly increases its efficiency [1, 2, and others]. This is explained by the fact that the thickness of the liquid film decreases as the gas velocity increases [3], which makes it possible to intensify the processes occurring in the liquid and gas. Equipment with descending single-pass flow, which is characterized by reduced hydraulic resistance [4], is finding increasing wider application in practice. However, there is still insufficient data on the hydrodynamics of such equipment.

Presented below are the results of experimental studies of the thickness and velocity of a water film for descending turbulent flow together with air in a vertical tube 30 mm in diameter. The spray density in the experiments varied over the range $\Gamma = (0.6\text{-}5) \cdot 10^{-3}$ m^2/sec, the air velocity varied from 3 to 13 m /sec, and the supplied air density varied by a factor of three. Visual observations showed that separation of drops from the surface of the film was not observed for the specified ranges of the flow-rate parameters. The experiments were performed on the device previously described [5]. The length of the experimental section was 2380 mm. The liquid film in the tube was supplied from a special generator through an annular slot having a width of one or two millimeters. Film thickness within the tube was measured by the probe method. Movement of the probe was accomplished by means of a micrometer screw and the film thickness was read off an indicator dial. The time of probe contact with the surface of the film was recorded by a special instrument in the form of an electronic relay. The detector design developed made it possible to to measure film thicknesses to an accuracy of 0.01 mm. Wave amplitude on the surface was determined from measured wave crests and troughs. The frequency of crossing the average level of film thickness was determined from the number of times the electronic device was triggered, which was recorded with a special sensor. In addition, the frequency spectrum over a given time was written on chart paper by means of a pen with an electromagnetic drive to which a signal was fed at the time the electronic device was triggered. The local thickness of the film at the crest of a wave and in the trough was determined at five points. The free path of the film up to the points of measurement were respectively: $l_1 = 250$ mm, $l_2 = 500$ mm, $l_3 = 750$ mm, $l_4 = 1000$ mm, and $l_5 = 1625$ mm.

The mean film thickness and the wave amplitude corresponding to a given free path were defined as

$$\delta_i = \frac{1}{2}(\delta_{ci} + \delta_{ti}),\ A = \frac{1}{2}(\delta_{ci} - \delta_{ti}). \tag{1}$$

The average thickness of the film over the entire surface of the experimental tube was determined from

$$\delta = \sum_{i=1}^{5} \delta_i l_i \Big/ \sum_{i=1}^{5} l_i. \tag{2}$$

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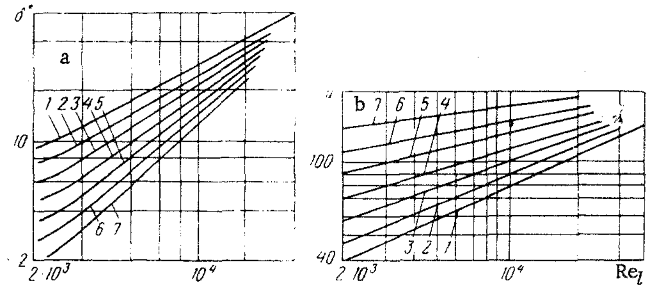

Fig. 1. Dependence of dimensionless average film thickness on Reynolds number of the liquid (a): 1) $Re_g = 0$; 2) 6000; 3) 10,000; 4) 14,000; 5) 18,000; 6) 22,000; 7) 26,000; and of the dimensionless average flow velocity of the film on Re_l (b): notation same as in (a).

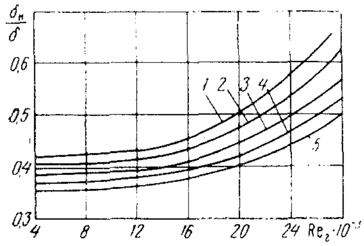

Fig. 2. Dimensionless thickness of unperturbed film layer for various free paths: 1) $l = 250$; 2) 500; 3) 750; 4) 1000; 5) 1625.

In addition, the average film thickness for the entire tube was determined by the supply cutoff method and the average flow velocity was determined by a volumetric method. Measurements of average film thickness and velocity in the absence of gas flow (see curves 1 in Figs. 1a and 1b) made it possible to establish the following dependence on the Reynolds number of the film for them:

$$\delta^* = 0{,}195\,\mathrm{Re}_l^{0{,}55}, \tag{3}$$

$$u = 1{,}28\,\mathrm{Re}_l^{0{,}45}, \tag{4}$$

which agree with other data [6, 7] within 15%.

The experiments showed that the average film thickness decreases with an increase in the gas flow rate and increases with an increase in liquid flow rate. The dependence of the dimensionless average film thickness on the Reynolds number of the liquid for fixed values of the Reynolds number of the gas is shown in Fig. 1a. On a log–log plot these relations are of a linear nature for the range of Reynolds numbers under consideration. The relationships shown in Fig. 1a are approximated by the following expression,

$$\delta^* = [0{,}359\exp(-0{,}1305\cdot 10^{-3}\,\mathrm{Re}_g) - 0{,}012] \times \\ \times \mathrm{Re}_l^{0{,}55+1{,}285\cdot 10^{-5}\mathrm{Re}_g}. \tag{5}$$

Thinning of the films as the gas flow velocity increases is associated with an increase in the average liquid velocity within the film because of transfer of energy from the gaseous core through the interface. The dependence of the dimensionless average flow velocity of the liquid in the film on the Reynolds number Re_l is shown in Fig. 1b. The figure makes it clear that the dimensionless velocity increases both with an increase in the Reynolds number of the liquid and with an increase in the Reynolds number of the gas, with the effect of the Reynolds number of the liquid on the average velocity of film flow decreasing as the Reynolds number of the gas increases. The experimental data shown in Fig. 1b is described by the following expression,

$$u = [1{,}362\exp(0{,}1405\cdot 10^{-3}\,\mathrm{Re}_g) - 0{,}896] \times \\ \times \mathrm{Re}_l^{0{,}45-1{,}25\cdot 10^{-5}\mathrm{Re}_g}. \tag{6}$$

It is well known [5, 7, 8] that the hydrodynamic parameters of a film depend on its free path. Figure 2 shows the dependence of the dimensionless thickness of an unperturbed layer of film on the Reynolds number of the gas for various free paths of the film. The parameter given, which determines the nature of the wave perturbation of the film, represents a rather complex relationship. It was established experimentally that the thickness of an unperturbed layer of film depends slightly on the Reynolds number of the liquid and decreases with an increase in gas velocity. However, it is necessary to point out that in the region of low gas flow rates ($Re_g < 10{,}000$) and high liquid flow rates ($Re_l > 20{,}000$) there apparently occurs some dependence of the thickness of the unperturbed layer on the Reynolds number of the liquid. The spread in the experimental points in the region indicated is about 40%. As the gas velocity increases, the average thickness of the film falls somewhat more rapidly than the thickness of an unperturbed layer. In addition, the average thickness of the film also decreases somewhat as the free path increases. What has been said above also explains the behavior of the relations shown in Fig. 2. The fact that the dimensionless thickness of an unperturbed film layer is independent of spray density makes it possible to correlate this thickness with the gas flow rate.

NOTATION

A	is the wave amplitude, mm;
δ	is the mean thickness of film, mm;
δ_u	is the thickness of undisturbed film layer, mm;
δ_c, δ_t	are the film thickness over waves crests and troughs, mm;
v, v_{Γ}	are the mean velocity of film and gas, m/sec;
d	is the tube diameter, m;
g	is the free-fall acceleration, m/sec^2;
ν	is the kinematic viscosity, m^2/sec;
l	is the mean free path length on film, mm;
δ^*	is the dimensionless thickness of film;
u	is the dimensionless velocity;
Re_l	is the Reynolds number for film;
Re_g	is the Reynolds number for gas.

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