THE DOWNWARD MOTION OF A LIQUID FILM IN VERTICAL TUBES IN AN AIR – VAPOR COUNTERFLOW

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Results from experimental investigation into the hydrodynamics of the downward motion of a liquid film in vertical tubes in an air–vapor countercurrent are presented. In addition, we have derived the theoretical relationships for the liquid-film thicknesses and the tube-"breakup" density.

The flow of liquid films in vertical tubes in a countercurrent with a gas or vapor occurs in various mass- and heat-exchange installations, and it happens on reversal of circulation in steam boilers and in circulatory evaporators, when a semireversal regime sets in [1, 2].

It is to certain problems of the hydrodynamics of such motion that this paper is devoted.

The tests were carried out on three installations. The first unit was an evaporator with two tubes 32.7 and 52.5 mm in diameter and 3 m in length; the second unit was a 24-tube evaporator whose tubes exhibited the following dimensions: d = 30 mm, L = 2.5. The third installation was used to measure the thickness of the liquid film by a method in which the flow of the liquid was suddenly shut off. The length of the experimental segment was 2017 mm, with an inside diameter of 32.7 mm. Water and sugar solutions were used as the working fluid in each of the installations. In the experiments with a boiling film, the heat flow varied from 6000 to 50,000 W/m^2 at a secondary-vapor pressure ranging from 1-2.55 bar. The adiabatic-flow experiments were carried out at an air density $\rho'' = 1.2$-$2.4\ kg/m^3$ and at a liquid viscosity $\mu' = 1 \cdot 10^{-3}$-$270 \cdot 10^{-3}\ N \cdot sec/m^2$.

A descending flow of a film in a countercurrent with a gas is set up both when the liquid swells to a constant level above the tube used in the experiment and when the liquid is poured over the upper lip of the tube. The liquid enters the tube from the top and is removed into measuring tanks at the bottom, where a volumetric method is employed to determine the "breakup" density of the tube.

The air is saturated with moisture as it is bubbled through the water and, after carefully separating out the water droplets, it is fed from the bottom into the experimental tube. Diaphragms are used to measure the water flow rate.

During the experiments with boiling film we measured the local values of the heat flow at various points along the tube. Plates were mounted on the tubes for this purpose to collect the condensate and to pass it along to the measuring tanks.

To determine the average thickness of the liquid film in tests involving air–water and air–sugar solution flows, we employed the familiar method of suddenly cutting off the flow, a method described in detail in [3, 4].

As soon as the two-phase liquid film attains the steady state, high-speed valves are used to shut off the experimental portion of the tube instantaneously, and the quantity of liquid is then measured. Special calibration tests were employed to determine the extent to which the liquid failed completely to run down from the tube walls. The error in the determination of the film thickness did not exceed 6%. The film thickness was defined as

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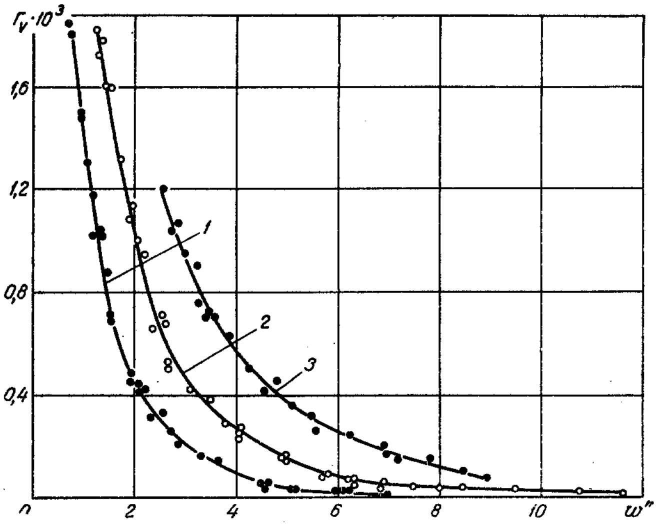

Fig. 1

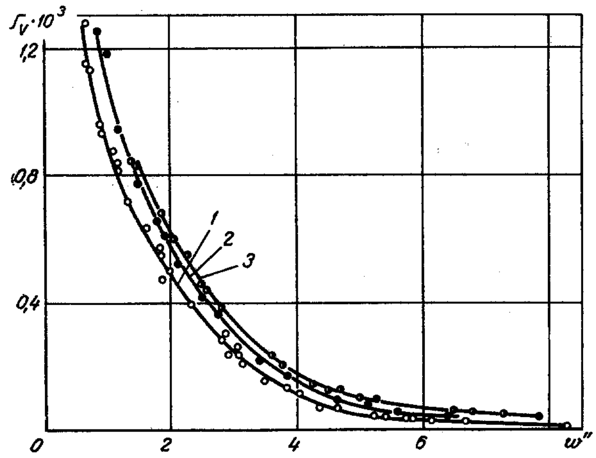

Fig. 2

Fig. 1. Volume density Γ_V (m^2/sec) versus density and velocity w" (m/sec) of gas (d = 52.5 mm): 1, 2) water – air, ρ'' = 2.33 and 1.22 kg/m^3; 3) water – vapor, ρ'' = 0.65 kg/m^3.

Fig. 2. Volume density Γ_V (m^2/sec) versus velocity w" (m/sec) of gas and density of liquid (d = 32.7): 1) water – air, ρ'', 1.22 kg/m^3; 2, 3) sugar solution – air, respectively, μ' = 22.10^{-3} N·sec/m^2, ρ' = 1230 kg /m^3 and μ' = 175·10^{-3} N·sec/m^2, ρ' = 1320 kg/m^3.

$$\delta = \frac{d}{2} - \sqrt{\frac{d^2}{4} - \frac{V}{\pi L}}.$$

The shearing stresses at the free surface were found from the formula

$$\tau_0 = \frac{\Delta P_{\mathrm{rel}}}{4L}(d - 2\delta).$$

The resistance factors for two-phase flow in a countercurrent were determined from empirical equations, by the method described in [6].

For purposes of visual observation and photography, a glass tube 600 mm in length was mounted ahead of the experimental section, and the stabilization segments in front of the experimental tube were 1800 mm in length.

The descending liquid-film flow in a countercurrent with a gas takes place along the "flooding" boundary when the tube is fed at the top from the liquid layer above the boiler tube, and that flow is determined by the hydrodynamic conditions below the point at which the liquid enters the tube. The maximum quantity of liquid entering the tube is closely related to the velocity of the gas at the tube outlet. For a given gas velocity and constant properties of the two-phase flow components, by pouring the liquid over the upper lip of the tube it is possible to achieve any "breakup" density lower than the maximum in the boiler tube. For a liquid "breakup" density below the maximum for a given gas velocity, the forces of friction exert no significant effect on the film thickness, nor on the magnitude of the "breakup" density.

The basic factor determining the process of liquid flow is the gas velocity; as the latter increases, there is an increase in the frictional shearing stresses at the phase separation boundary $\tau_0 = \xi\rho''[w''_{\mathrm{rel}}]^2/2$, the thickness diminishes, and so does the velocity of liquid-film motion.

For a water – air system when P_g = 1 bar we observed visually the submersion of the liquid film as the Reynolds number of the air increased, and there was intensified wave formation. With a velocity of approximately 10 m/sec for the air the water film broke up into drops which remained on the surface and began to tremble under the action of the air. It was only as the air reached a velocity of about 15 m/sec that the inversion of the flow set in, i.e., the liquid began to flow from the bottom to the top.

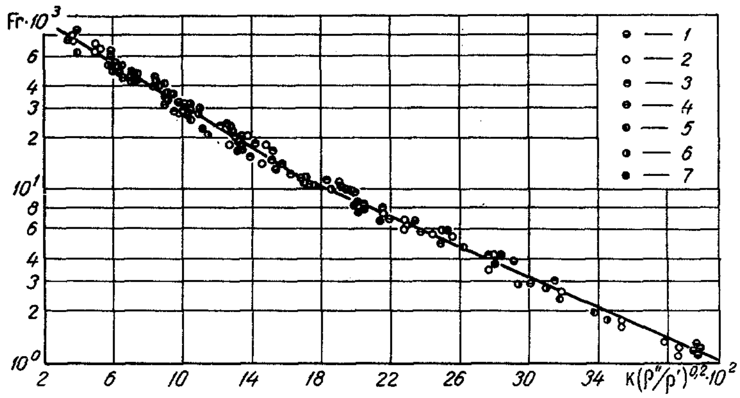

Fig. 3. Generalization of experimental data in system $Fr = f[K(\rho'/\rho'')^{0.2}]$: d – 52.5 mm: 1, 2) water–air $\rho'' = 2.2$-2.4 and 1.2-1.24 kg/m^3; 3) water–vapor $\rho'' = 0.6$-0.68 kg/m^3 d – 32.7 mm: 4) water–air $\rho'' = 1.22$ kg/m^3; 5 and 6) sugar solution–air $\mu' = 21$-$39 \cdot 10^{-3}$ and 100-$260 \cdot 10^{-3}$ N·sec/m^3; 7) water–vapor $\rho'' = 0.6$-0.68 kg/m^3.

For a sugar solution exhibiting a viscosity of $160 \cdot 10^{-3}$ N·sec/m^2, with the air moving at a speed higher than 6.5 m/sec, we visually observed the appearance of circular waves moving upward along the film surface, with the liquid moving downward at the wall. With gas velocities close to a critical value, the wave amplitude increases, and at a velocity of about 11-12 m/sec undulating segments of the liquid are suspended from the film surface, with a slight descending motion continuing in the layer at the wall. It is only with an air velocity on the order of 16 to 17 m/sec that the entire liquid film begins to move upward.

With a drop in the gas velocity there is a reduction in the frictional shearing stresses, the "breakup" density increases, and the liquid begins to separate from the wall and move in the form of a jet. At liquid velocities close to those at which bubbles are swept downward, the semireversed motion changes completely into reversed motion.

The film flows downward in a specific interval of gas–liquid velocities. The lower bound of this interval is the velocity at which the bubbles are entrained by the liquid, while the upper bound is the inversion of the flow which sets in for adiabatic flows when the two-phase flow stability criterion reaches a value of $K \simeq 3.2$, which agrees with the data of [7]. In the case of a boiler tube, as the heat flow increases there is an increase in the velocity of the vapor at the tube outlet and there is a corresponding drop in the liquid "breakup" density. With a drop in the "breakup" density, the thickness of the liquid film diminishes, and sections of the heating surface are left bare. In turn, this leads to a drop in the heat flow and to an increase in the quantity of liquid entering the tube. The boiler tube operates in a pulsating regime when the vapor velocities reach critical values.

The effect of the gas density on the magnitude of the volume "breakup" density Γ_V is shown in Fig. 1. Given a constant gas velocity, the magnitude of the volume "breakup" density diminishes as the gas density increases and the space within which the semireversed flow can exist stably is reduced.

We see from Fig. 1 (curve 2) and Fig. 2 (curve 1) that the volume "breakup" density of the liquid for a tube 52.5 mm in diameter is greater than for a tube 32.7 mm in diameter, given the same velocity and density of the air. With an increase in the tube diameter, the value of Γ_V increases and the space within which the semireversed flow can exist stably is expanded.

To determine the effect of viscosity and liquid density on the volume "breakup" density, we carried out tests on sugar solution–air flows in a tube 32.7 mm in diameter at $P_2 = 1$ bar (Fig. 2). We see from Fig. 2 that the wetting density for the solutions varies only slightly in comparison with the water, even though the viscosity varies greatly. Since the liquid film moves by gravitation, the increase in Γ_V is apparently explained not by the viscosity of the solution but by the increase in the liquid density from 1000 kg/m^3 for water to 1320 kg/m^3 for a sugar solution with a viscosity of $\mu' = 175 \cdot 10^{-3}$ N·sec/m^2. The thickness of the film increases as the viscosity of the solution increases, but the flow velocity for the film diminishes. The fact that Γ_V changes only slightly with a change in the viscosity of the liquid within the indicated limits can apparently be explained by these mutually offsetting factors.

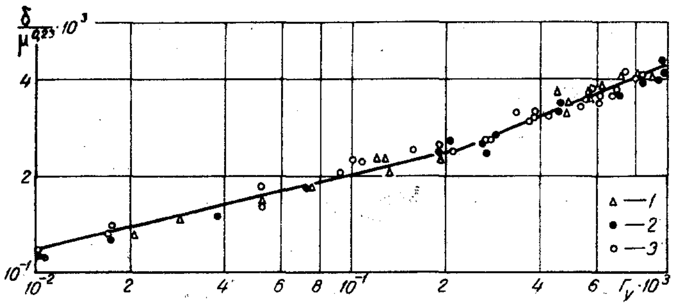

Fig. 4. Generalization of experimental data in coordinates $(\delta/\mu^{0.23})(m^3/N\cdot sec)$ – $\Gamma_V(m^2/sec)$ (d = 32.7 mm, ρ'' 1.22 kg/m^3): 1) water–air $\mu' = 1\cdot 10^{-3}$ $N\cdot sec/m^2$; 2 and 3) sugar solution–air $\mu' = 21\text{-}39\cdot 10^{-3}$ and $100\text{-}260\cdot 10^{-3}$ $N\cdot sec/m^2$.

We were unable to determine the effect of surface tension on the process in the experiment, since there was only a slight change in the surface tension – from $58\cdot 10^{-3}$ to $76\cdot 10^{-3}$ N/m.

To generalize the experimental data so as to determine the "breakup" density of the liquid in the tubes in the case of a descending film flow in a gas counterflow we adopted the critical relationship which included all of the above-considered factors which determine the process of motion:

$$\mathrm{Fr} = f\left[\mathrm{K}; \frac{\rho''}{\rho'}\right], \tag{1}$$

K is the stability criterion for the free surface of the two-phase flow and it reflects the ratio of the dynamic head to the gravity forces which act on the liquid film.

We see from Fig. 3 that the experimental data pertaining to the vapor–water and air–sugar solution flows are properly covered by the following equations for tubes of various diameters in regions of stable semireversed flow:

for Fr > 0.012

$$\mathrm{Fr}_1 = 0.129 \exp - 14.14\,\mathrm{K}\left[\frac{\rho''}{\rho'}\right]^{0.2}, \tag{2}$$

for Fr < 0.012

$$\mathrm{Fr}_2 = 0.0653 \exp - 10.12\,\mathrm{K}\left[\frac{\rho''}{\rho'}\right]^{0.2}. \tag{3}$$

The value of Γ_V from Eqs. (2) and (3) is equal to

$$\Gamma_{V_1} = 0.404\, d^{1.5} \exp - 8.054 \frac{w''[\rho'']^{0.7}}{\sigma^{0.25}[\rho' - \rho'']^{0.25}[\rho']^{0.2}}\ \mathrm{m^2/sec}, \tag{4}$$

$$\Gamma_{V_2} = 0.2046\, d^{1.5} \exp - 5.717 \frac{w''[\rho'']^{0.7}}{\sigma^{0.25}[\rho' - \rho'']^{0.25}[\rho']^{0.2}}\ \mathrm{m^2/sec}. \tag{5}$$

If we neglect the value of ρ'' in the expression $\sqrt[4]{\rho' - \rho''}$, for engineering calculations of the volume "breakup" density of the liquid at the inlet to the tube for the case of semireversed motion we can recommend the following formulas:

$$\Gamma_{V_1} = 0.404\, d^{1.5} \exp - 8.054 \frac{w''[\rho'']^{0.7}}{\sigma^{0.25}[\rho']^{0.45}}\ \mathrm{m^2/sec}, \tag{6}$$

$$\Gamma_{V_2} = 0.2046\, d^{1.5} \exp - 5.717 \frac{w''[\rho'']^{0.7}}{\sigma^{0.25}[\rho']^{0.45}}\ \mathrm{m^2/sec}. \tag{7}$$

Semenov [5] theoretically derived the following equation to determine the film thickness for the flow of a liquid in a counterflow with gas:

$$\Gamma_V = \frac{\rho' g - \varphi}{3\mu'}\delta^3 - \frac{\tau_0}{2\mu'}\delta^2. \tag{8}$$

In determining the film thickness from Eq. (8) we have to find the pressure difference ΔP_{br} across the tube experimentally. The equation agrees with our data only for small thicknesses of the liquid film.

The film thickness in the case of descending flow in a gas counterflow is affected primarily by the viscosity of the liquid and the relationship between the gravitational forces and the shearing stresses at the film surface. The shearing stresses retard the film flow, the film becomes thicker, and its velocity is reduced.

With an increase in the "breakup" density there is an increase in the thickness and velocity of the film; when the viscosity increases, the thickness increases correspondingly, but the velocity of the flow diminishes.

In generalizing the experimental data to determine the film thickness we used the relationship $\delta = f[\mu'; \Gamma_V]$.

The effect of the gravitational forces and shearing stresses is accounted for by the volume "breakup" density which, for the regime under consideration, is a function of the quantities

$$\Gamma_V = f[\mu'; \rho'; \sigma; w''; d; \rho'']. \tag{9}$$

The experimental data on film thickness (Fig. 4) are well generalized by the following equations:

for Fr > 0.012

$$\delta_1 = 7.13\,\mu^{0.23}\Gamma_V^{0.4}, \tag{10}$$

for Fr < 0.012

$$\delta_2 = 17.02\,\mu^{0.23}\Gamma_V^{0.23}. \tag{11}$$

The effect of viscosity is identical throughout the entire range of generalization, since the film flows in a turbulent manner throughout the entire region of stable semireversed motion. With a drop in the shearing stresses, the turbulent of the liquid is maintained as a result of the increased thickness of the liquid film, while in the region in which $Re_{film} < Re_{cr}$, we have observed with the naked eye the wave formation at the surface of the film which results from the action of the shearing stresses.

The presence of two regions in the generalization of the experimental data is explained by the differing effect of the shearing stresses on the film flow. As a result of our visual observations, the transition from one region to another can be explained by the onset of substantial wave formation at the surface at the surface of the film.

On the basis of Eqs. (6), (7), (10), and (11) we can calculate the maximum possible "breakup" density and the liquid film thickness for film counterflow equipment prior to the "flooding" regime and for the case of semireversed circulation.

NOTATION

δ	is the liquid film thickness;
L	is the length of the experimental tube segment;
d	is the tube diameter;
V	is the volume of the liquid collected in the experimental segment of the tube;
ΔP_{br}	is the pressure difference across the experimental tube segment during liquid breakup;
τ_0	is the frictional shearing stresses at the free surface;
ξ	is the resistance factor;
$w''_{rel} = w'' + w'_{bound}$	is the relative gas velocity;
w'_{bound}	is the velocity of the liquid at the phase boundary of separation;
ρ''	is the gas density;
ρ'	is the liquid density;

μ''	is the dynamic viscosity of the gas;
μ'	is the dynamic viscosity of the solution;
ν'	is the kinematic viscosity of the solution;
$\varphi = 4\Delta P_{br}/L$	is the pressure gradient;
P_2	is the pressure in the space above the tube;
Γ_V	is the volume "breakup" density of the liquid;
$K = w''\sqrt{\rho''}g/\sqrt[4]{g^3\sigma(\rho' - \rho'')}$	is the stability criterion for the two-phase flow;
$Fr = \Gamma_V/\sqrt{gd^3}$	is the Froude number;
$Re_{film} = 4\Gamma_V/\nu'$	is the Reynolds number for the film;
Re_{cr}	is the Reynolds number which denotes the boundary of the transition from laminar film flow to a turbulent regime;
g	is the free-fall acceleration;
σ	is the surface tension;
w''	is the true gas velocity.

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