FLOW OF A LIQUID FILM IN A COCURRENT UNDER THE ACTION OF EXTERNAL FACTORS

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Due to the extensive realization in various fields of technology over many years stratified gas–liquid flows are a subject of comprehensive study. However, in spite of the fact that a considerable number of scientific works [1-5] are devoted to the combined movement of liquid and gas, data known currently for the interaction of a liquid film with a gas cocurrent in actual gas dynamic systems are very limited. In the main this is determined by the fact that in the majority of cases researchers consider a given problem in an idealized situation when processes of film flow are studied without considering the influence of factors which are external in the nature of their effect on a thin layer of liquid. A summary of the results of these studies [5] made it possible to determine a well-founded two-parameter dependence of heterogeneous flow characteristics on liquid flow rate in a film and with air flow Reynolds number $Re_{x_2} = u_{2H}x/\nu_2$, expressed in terms of longitudinal coordinate x, where u_{2H} is air velocity at the outer limit of the boundary layer; ν_2 is air kinematic viscosity. Meanwhile, presence during operation of various industrial equipment of surface flow vibrations of a liquid, a change in its wettability, variation of turbulence characteristics, and longitudinal velocity of the accompanying phase, may markedly affect the final parameters of working systems [6].

The basic principles are shown in [7] for constructing a method and model for calculating stratified gas–liquid flows which makes it possible to consider the effect of an air pressure gradient on average thickness of a liquid layer, and some calculated data are provided. Results are given in the present work for experimental studies of flow of a water film under the influence of an air stream with presence of a gas phase pressure gradient dp_2/dx and different levels of its turbulence $Tu_{2\infty}$.

Experiments were performed in a unit including a direct-flow aerodynamic pipe and a device for liquid supply and removal. In the working section of the pipe air flow velocity was realized up to 35 m/sec, and water flow rate expressed in dimensionless form in terms of Reynolds film number $Re_1 = G_1/\mu_1$ (G_1 is liquid mass flow rate relative to the film width; μ_1 is liquid dynamic viscosity coefficient) varied from 0 to 860. The lower panel of the working part was the liquid flow surface at which film thickness gauges were placed. In order to record liquid layer parameters a measuring system was used based on the method of local electrical conductivity using slit resistor primary converters.

In order to model liquid flow with different air pressure gradients the upper panel of the working section of the experimental unit was made flexible, which made it possible, by regulating the length of support rods, to create the required shape of the flow channel of the aerodynamic pipe.

Using these structural possibilities of the unit a series of experiments was carried out whose results are presented in Fig. 1. Measurements of the average liquid film thickness $\bar{\delta}_1$ were carried out with identical initial flow conditions (undisturbed flow velocity $u_{2\infty}$ = 20 m/sec and liquid flow rate $Re_1 = 192$), but different values of air pressure gradient (lines 1-5 relate to dp_2/dx = 17.7, 11.5, 0, −14.2, −34.4 kg/m³). Shown in Fig. 2 is a comparison of the wave profiles of the film surface (change in local liquid layer thickness δ_1 over the flow x) with $u_{2\infty}$ = 20 m/sec, Re_1 = 192 obtained in a gradient dp_2/dx = 11.5 kg/m³ (thin line) and a gradientless dp_2/dx = 0 (bold line) air flow.

Analysis of the experimental data makes it possible to assess the marked effect of a constantly operating positive pressure gradient for the light phase on the nature of liquid flow. Proceeding from a physical model for viscous interaction of two flows with different properties with a diffusion flow presence of positive derivative dp_2/dx causes in addition

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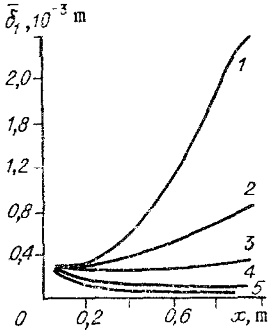

Fig. 1

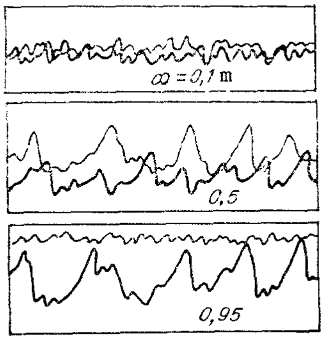

Fig. 2

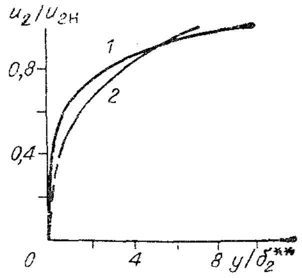

Fig. 3

to the effect of flow over a rough wall (wavy roughness in this case may exceed by a factor of several tens the acceptable roughness) a decelerating effect of the pressure drop which promotes a reduction in dynamic load of air at the liquid surface. To the known position of the influence of a positive pressure gradient on flow in boundary layers should be added the fact that presence of wavy movement at the film surface and transport by air of a water droplet stripped from the crest of a wave leads to more intense energy dissipation for two-phase flow. A change in the distribution of air velocity over the normal to the wall (Fig. 3) with $dp_2/dx = 11.5$ kg/m^3, $u_{2\infty} = 20$ m/sec, and $x = 0.5$ m ($Re_1 = 0$, 192 are lines 1 and 2) showed that the two-phase nature of flow promotes a reduction in the fullness of the velocity profile. The value of shape parameter $H_2 = \delta_2^*/\delta_2^{**}$, corresponding to a single-phase turbulent layer $H_2 = 1.48$ increases to $H_2 = 1.83$ in a heterogeneous flow. By analogy with conclusions about an early change-over with combined movement of two phases of laminar flow into turbulent flow [5], the results obtained make it possible to talk about the reinforcing effect of the pressure gradient with presence of a thin layer of liquid at the flow surface, which is conducive to premature separation of the flow.

With a negative pressure gradient for the gas medium under the test conditions obtained in the first case the clearly defined effect of a change in air velocity on the liquid flow is absent. Probably the reason for this is an increase in liquid viscosity compared with the gas which prevents an increase in the velocity of movement in a thin layer, and also less intense changes along the flow in the value of tangential stress, which finally leads to a reduction in the sensitivity of liquid film parameters to longitudinal acceleration of the air mass.

A deeper analysis of the effect of air pressure gradient on liquid movement is carried out on the basis of the results of experiments in which physical modeling of liquid film flow was performed with different initial conditions. An estimate of the effect of these factors on average liquid layer thickness $\bar{\delta}_1$ was carried out by means of the integral parameter

$$m_1 = \rho_1 \int_0^L \bar{\delta}_1 \, dx,$$

where ρ_1 is liquid density; L is liquid flow surface length. The value of m_1 characterizes the mass of liquid related to the channel width found at the flow surface. A change in m_1

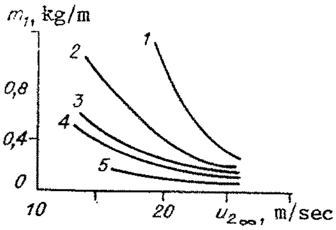

Fig. 4

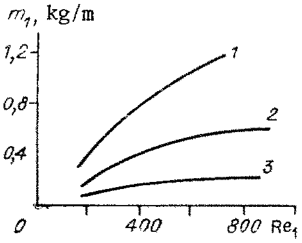

Fig. 5

in relation to dp_2/dx with $Re_1 = 200$ (lines 1-5 in Fig. 4 relate to $dp_2/dx = 17.7$, 6.8, 0, −7.9, −31.6 kg/m³) and with $u_{2\infty} = 25.5$ m/sec (lines 1-3 in Fig. 5 for $dp_2/dx = 25.5$, 0, −31.6 kg/m³) shows that the effect of a pressure gradient on liquid flow is governed by its value and sign. It is more marked with low undisturbed flow velocities and higher liquid flow rates in the film. With a reduction in pressure gradient to negative values the effect of these factors is weakened.

In industrial units in whose channels stratified two-layer flows form, as a rule various power devices are used in order to accelerate the air (for example, turbomachines) which promote considerable turbulence. In view of this there is an undoubted interested in studying the effect of turbulence of external flow $Tu_{2\infty}$ on liquid film parameters. For this purpose using single-plane grills, which are passive turbulence generators, different levels of turbulent disturbances of the air mass were established in the aerodynamic pipe whose values were determined by a thermoanemometer system 55M from the firm DISA Electronic.*

The criterion used for estimating the effect of external turbulence of the light phase on local film parameters was the start of forming at the liquid surface disturbance waves which are easily observed in an experiment and are distinguished over a broad spectrum of wave formation by high amplitude and a broad wave front. Presented in Fig. 6 are experimental results (lines 1-8 relate to $u_{2\infty} = 15$, 16, 17, 18, 20, 22, 25, 28 m/sec), which show that the liquid flow rate Re_1 with which a disturbance wave starts to generate depends on velocity and the degree of gas cocurrent turbulence. The turbulence has a marked effect on the structure of the wavy film surface with low air velocity, and with a gradual increase in velocity this effect degenerates. Probably the reason for the effect observed should be found in the nature of change in disturbances in the boundary layer which depends on the level of turbulence and external flow velocity. Statements in [8, 9] indicate that according to features of the distribution of pulsating components of velocity the kinetic energy of turbulence in the layer increases toward the wall more intensely, the lower the level of external disturbances. At the same time, an increase in air flow velocity promotes a reduction in boundary turbulence. As a result of this even with low turbulence of the outer flow in the boundary layer itself the air phase generates powerful disturbances which are strengthened with approach toward the film surface and which promote wave formation. In view of the initial surface tension as liquid moves in the longitudinal direction there is supply of wave movement energy (conversion of ripples into coarse and squally waves [5]).

The nature of the effect of turbulence of external flow determined in Fig. 6 on the wavy boundary of the liquid and gas may probably be explained by considering the process of wave movement development of the film surface as the result of transfer of air flow energy to the liquid which is a combination of energy caused by translational motion of the phases and disturbance energy generated by pulsations of the air mass close to the film surface. Oscillograms in Fig. 7 demonstrate wave profiles of a thin liquid layer with an air flow velocity $u_{2\infty} = 17$ m/sec, water flow rate in the film $Re_1 = 170$, but different levels of turel of turbulence in the range of air mass velocities with the effect of external disturbances is particularly perceptible, there is some increase in average film thickness (Fig. 8) caused by a reduction in wave amplitude and a reduction in the amount of liquid transferred into them ($Re_1 = 192$, $u_{2\infty} = 15$ m/sec, $Tu_{2\infty} = 6.25$ and 0.99% are points 1 and 2).

Finally, we draw the following conclusions. Physical modeling of liquid movement in an air flow gradient made it possible to establish the marked changes in average film thickness and wave disturbances of its surface under the effect of a positive pressure gradient. In this case with an increase in longitudinal flow coordinate the thickness of the liquid layer

*With the participation of A. A. Bondarts.

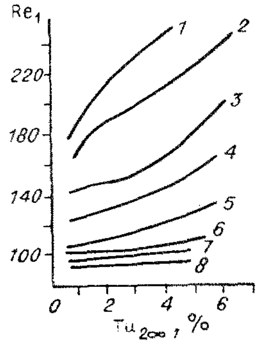

Fig. 6

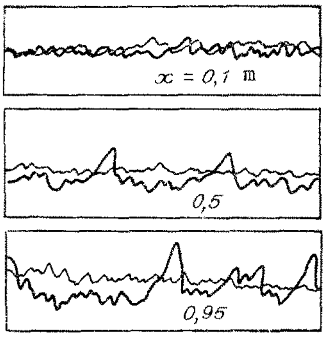

Fig. 7

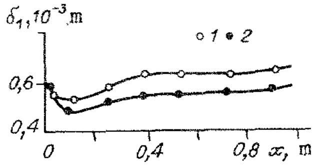

Fig. 8

increases, but there is a reduction in nonuniformity of the phase interface. A study of the effect of turbulence of external flow on the nature of liquid movement shows that the elements of generated waves and average film thickness depend on the level of disturbed air mass turbulence. With low and moderate values an increase in the level of turbulence leads to a reduction in a wavy surface for the gas and liquid interface, and an increase in average liquid layer thickness.

The results obtained provide a basis for suggesting the possibility of controlling flow processes in stratified flows with the aim of providing the optimum operating regimes for different industrial units. The attempt made by the author to substantiate the effect of external factors detected on the nature of gas–liquid interaction undoubtedly does not give a sufficiently complete picture. In all probability in order to expose the true mechanisms for this effect more fundamental studies drawing on modern experimental and theoretical methods and equipment are necessary.

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STRUCTURE OF A RISING THERMAL

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In [1], the motion was considered for a mass of air heated to a high temperature and initially at rest in a spherical volume under gravity. At the start of the motion, the volume is transformed to a buoyant vortex ring. The turbulent transport in the vortex ring motion is described by a semiempirical theory, which incorporates the effects from the velocity and temperature inhomogeneity, which tend to suppress radial turbulent diffusion fluxes at the core. Numerical calculations have given the distributions for the velocity, vorticity, temperature, and heat fluxes. The toroidal vortex is clearly seen, whose disposition in space coincides with the toroidal temperature pattern.

At an early stage, the main part is played by inertial dynamic effects associated with the generation of the vorticity, which transforms the spherical volume of light gas into a rising vortex ring. The effects from turbulent exchange in the initial stage are neglected because they are slight. The ring formation is described by gas-dynamic equations, which are solved numerically via the [2-4] scheme, which has low scheme viscosity. The gas-dynamic parameter patterns calculated for the formation of the toroidal vortex act as initial ones for calculating the flow structure in the next stage.

Our numerous calculations on structures in thermals have shown that the vortex flow has a decisive effect on the dynamics. One has anisotropy in the turbulent transport, with the turbulent fluxes of heat and momentum diminishing toward the ring axis, which means that the form of the thermal persists for a long time during the rise, while the cross-sectional area of the core increases somewhat, as is observed in [5].

Later calculations were performed on these rings without allowance for the turbulent exchange at the stage of developed vortex motion, which showed that there are only minor differences in the height to which they rise. This shows that there is a decisive influence from inertial dynamic effects associated with the generation of the vorticity field under gravity as regards the rise of a large-scale thermal formation in the atmosphere.

1. This method is applied to experiments on thermals rising in the atmosphere [6] and under laboratory conditions [7]. The velocity and temperature patterns have been calculated without allowance for the turbulent transport. Those patterns have then been used to determine the turbulent characteristics on the assumption of local balance in the turbulent motion. One can judge the justification for this approximation from a comparison with experiment.

We used an r, z, φ cylindrical coordinate system. The z axis is directed in the opposite sense to the gravitational acceleration. All the functions are dependent only on r and z. The gas-dynamic equations are

$$\frac{\partial}{\partial t}\rho+\operatorname{div}(\rho\mathbf{V})=0,\ \frac{\partial}{\partial t}\mathbf{V}+(\mathbf{V}\cdot\nabla)\mathbf{V}=-\frac{1}{\rho}\nabla p+\mathbf{g},$$
$$\frac{\partial}{\partial t}\left(\rho\varepsilon+\rho\frac{V^2}{2}\right)+\operatorname{div}\left[\mathbf{V}\left(p+\rho\varepsilon+\rho\frac{V^2}{2}\right)\right]=0,$$
$$p=(\gamma-1)\rho\varepsilon,\ \varepsilon=c_VT,\ \mathbf{V}=(U,\ V). \tag{1.1}$$

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