STATISTICAL CHARACTERISTICS OF THE TEMPERATURE FIELD IN THE PIPE FLOW OF A GAS – WATER MIXTURE

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An experimental study of the statistical characteristics of the temperature field for a flow of a water and gas mixture in a pipe discloses a significant increase in the turbulent transport coefficient and a change in the structure of the water flow in the presence of the gaseous phase.

Two-phase turbulent flow is frequently encountered in present-day engineering. The pattern of two-phase flow differs qualitatively from that of single-phase flow. Chiefly, a difference is observed in the values of the viscous friction and average heat transfer. In the case of a cavitating flow of a water–gas mixture in a pipe, for example, elevated pressure differentials [1] and average heat transfer [2] are observed.

The mechanism of two-phase flow is considerably more complex than that of single-phase flow. However, many aspects of the two flows are analogous, and certain methods used to investigate single-phase turbulent flows can be applied to the investigation of two-phase flow. In the present study we have attempted to use temperature fluctuation measurements to study the structure of a two-phase nonisothermal flow. The presence of gas bubbles of large radii ought to effect significant changes in the structure of the turbulent temperature fluctuations by comparison with the flow of a single-phase fluid.

The experiments were conducted on an atmospheric-pressure test stand. The distillate circulation loop includes a centrifugal pump, an experimental test section, a tubular cooling unit, and a distillate receptacle containing an auxiliary cooling coil. The gas (nitrogen) is injected at the entrance to the experimental section from a cylinder through a reducer and a special orifice plate, which permits a constant volumetric flow rate to be maintained in acoustic streaming when a constant pressure is maintained at the entrance to the plate. During operation the pressures are monitored at the entrance and exit of the orifice plate. Plates having different orifice cross sections permitted the gas flow rate to be changed.

The experimental section represents a vertical pipe with an inside diameter of 49.8 mm and length of 2.5 m. A heat flow is produced by a Nichrome filamentary heater double-wound around a glass-micanite and glass-cloth electrical insulation layer. Asbestos wool is used for thermal insulation.

The inner surface of the pipe was reamed to a sixth-class finish, ensuring its smoothness in the investigated range of Reynolds numbers Re_0.

At a distance of 48 diameters from the tube entrance and 30 diameters from the initiation of heating two thermocouples were inserted in the water flow in order to investigate the temperature field. The thermocouples were moved in the flow cross section and relative to one another in the plane of the flow cross section by means of a special thermocouple probe, which allowed the thermocouples to be positioned with 0.05 mm error at any point of the flow in the cross section to be measured.

The thermocouples were fabricated from Chromel–Alumel wire 0.1 mm in diameter and were placed in a stainless steel capillary having an outside diameter of 0.5 mm and wall thickness of 0.1 mm. The thermocouple beads were welded by an electric-arc technique and were inserted in the flow without protective insulation. The entry and exit sites of the thermoelectrodes in the capillaries were sealed with epoxy resin. The diameter of the thermocouple beads was no more than 0.2 mm. This feature made it possible

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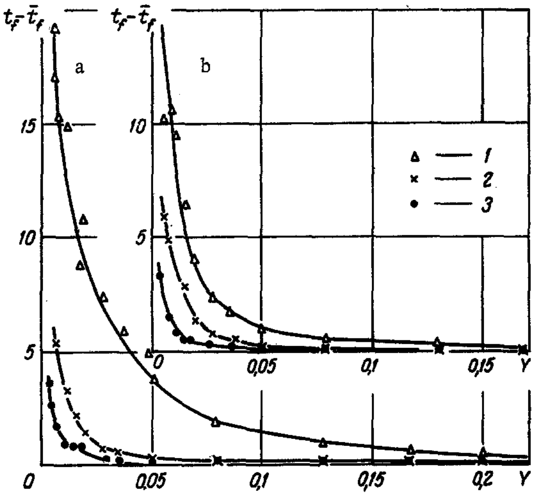

Fig. 1

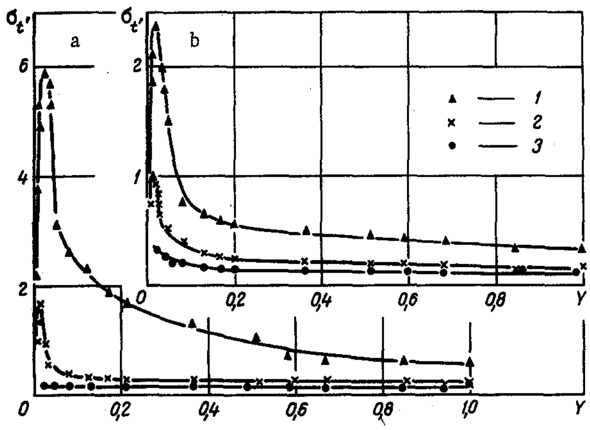

Fig. 2

Fig. 1. Average temperature fields. a) $V_W = 1.44$ m^3/h; b) 2.38 m^3/h. 1) $V_g = 0$; 2) 0.14 nm^3/h; 3) 0.72 nm^3/h. $(t_f - \bar{t}_f)$, °C.

Fig. 2. Temperature fluctuation intensity distribution. a) $V_W = 1.44$ m^3/h; b) 2.38 m^3/h. 1) $V_g = 0$; 2) 0.14 nm^3/h; 3) 0.72 nm^3/h. σ_t, °C.

TABLE 1. Experimental Relations of the Volumetric Flow Rates of the Water and Gas in the Investigated Cross Section

V_W, m³/h	V_g, m³/h		
	0	0,14	0,72
1,44	0	5,3%	20%
2,38	0	3,8%	15%

to measure the temperatures at distances of as little as 0.1 mm from the wall. The thermal lag of these thermocouples was small and distorted the fluctuations only at high frequencies, the contribution of which to the total fluctuation energy was small. The lag of thermocouples of this type in a flow of pure water has been analyzed in [3]. It is essential to note that in a two-phase flow with a volumetric gas content of at most 20% the thermocouple lag does not have too pronounced an effect on the measurement results.

The apparatus and procedure used to measure the average temperature fields and statistical characteristics of the temperature fluctuations are described in [4].

The investigation was carried out for two water volumetric flow rates (1.44 and 2.38 m^3/h) and for the following nitrogen flow rates: 0, 0.04, and 0.2 m^3/h, or 0, 0.14, and 0.72 nm^3/h.

The relative volumetric flow rates for the gas and water at the measurement site differed under different conditions and are summarized in Table 1; the temperature of the mixture was 10°C.

The investigations of the time-average temperature fields showed (Fig. 1) that even for a very slight gas content by volume the average-temperature gradients decrease sharply in the direction of the normal to the wall. The thermal transport coefficient and heat-transfer coefficient are observed to increase (the temperature in the pipe wall was not measured in the experiments, so that the precise quantitative increase of the heat could not be measured). The indicated increase in the turbulent heat transfer cannot be attributed solely to an increase in the average flow velocity (if this were the case, the flow velocity would have to increase severalfold). Clearly, the presence of the gas sharply alters the turbulent structure of the flow. One explanation could be a possible reduction in the effective molecular viscosity of the two-phase flow or, in other words, an increase in the effective Reynolds number Re_0. The viscosity reduction can be explained by the presence at the boundaries between the liquid vortices (between the liquid layers) of a medium (nitrogen) having a kinematic viscosity much smaller than the viscosity of the main flow. The measurements showed that the increase in the pressure differential in the pipe due to the presence of the gaseous phase is inconsequential.

The analysis of the statistical characteristics of the temperature fluctuations reveals to some extent the immediate cause of the increase in the diffusion properties of a two-phase turbulent flow. The gaseous

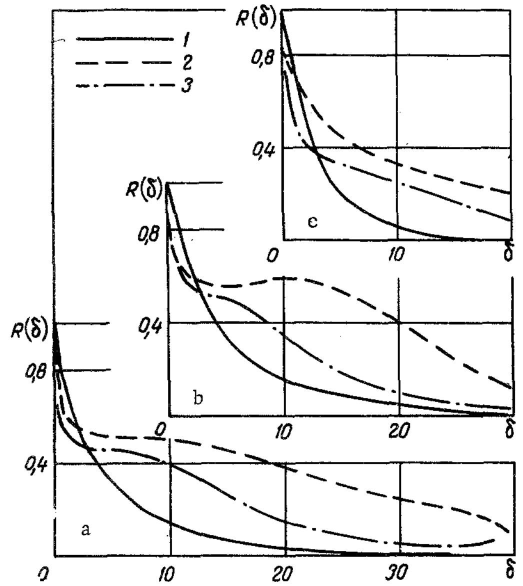

Fig. 3

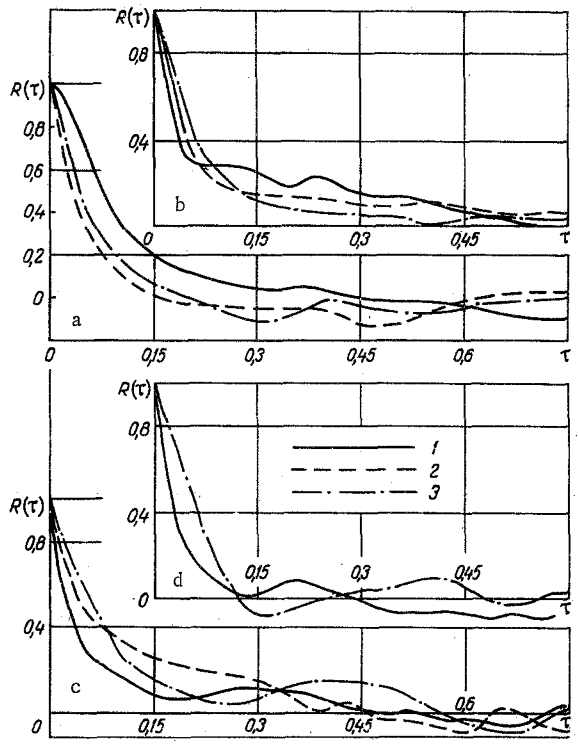

Fig. 4

Fig. 3. Spatial correlations for V_w = 1.44 m³/h. a) Y = 1.0; b) 0.5; c) 0.2. 1) V_g = 0; 2) 0.14; 3) 0.72 nm³/h. δ, mm.

Fig. 4. Autocorrelation coefficients for V_w = 1.44 m³/h. a) Y = 0.004; b) 0.2; c) 0.5; d) 1. 1) V_g = 0; 2) 0.14; 3) 0.72 nm³/h. τ, sec.

phase exerts the strongest influence on the intensity of the temperature fluctuations. It is seen in Fig. 2a and b that the presence of even a minute quantity of gas abruptly lowers the temperature fluctuation intensity over the entire flow cross section. The intensity maximum observed in single-phase flow degenerates, and for large gas contents (~20%) the fluctuation intensity becomes almost constant over the entire flow cross section.

The probability distribution function for the temperature fluctuation amplitude in two-phase flow, as the measurements indicate, is the same as in single-phase flow, differing very little from a normal Gaussian law.

The values of the spatial correlation coefficients obtained with the two thermocouples spaced at opposite ends of chords for r/r_0 = 0, 0.5, and 0.8 vary as a function of the percentage of gaseous phase in the flow (see Fig. 3). The larger the relative volumetric flow rate of gas, the higher will be the spatial correlation coefficients. Moreover, a qualitative change is observed in the behavior of the dependence R(δ). Whereas the variation of R(δ) in a single-phase flow has a smoothly decreasing character with increasing δ, with a gaseous phase present there is an abrupt jog characteristic of the presence of vortices of two sharply disparate dimensions. With the injection of gas into the flow a great many large vortices appear, which are clearly commensurate with the average diameter of the gas bubbles. The greater the volumetric gas content, the larger will be the contribution of the gas bubbles to the spectrum of turbulent perturbation scales. For a gas content of ~20% the integral turbulence scale attains one fourth the radius at the center of the pipe and is as much as four times the corresponding scale for a single-phase flow.

The presence of the gaseous phase is also strongly felt in the autocorrelation function for the temperature fluctuations (Fig. 4). At the center of the pipe the autocorrelation coefficients in a two-phase flow are higher than in the single-phase counterpart for identical lag times $\tau < T_E$, where $T_E = \int_0^\infty R(\tau)d\tau$. This situation is physically consistent with the data on the transverse spatial scales. An increase in the spatial scales results in greater correlation times. The pattern changes somewhat as the pipe wall is approached.

The effect of the second phase diminishes. Near the wall ($y/r_0 = 0.004$) the gaseous phase is observed to have the converse influence. Here the presence of the gas decreases the autocorrelation coefficients. Clearly, the intensified turbulence of the gaseous medium tends to break down part of the so-called laminar substrate.

On the basis of the data obtained and the application of conventional relations we can explain the physical nature of the gaseous phase and its influence on the structure and heat-transfer processes in a two-phase turbulent flow. For the gas contents that prevailed in our experiments, clearly, cavitating flow takes place. The fluctuation spectrum is augmented with the energy of vortices having scales greater than the root mean square vortex scale in a single-phase flow. This fact results in an increase of the vortex lifetimes, while scarcely disturbing the stochastic nature of the vortices; the latter result is implied by the results of measurements of the distribution function for the fluctuation amplitudes. It is known from [5] that the turbulent thermal transport coefficient is proportional to the Lagrangian lifetime T_L of the temperature perturbations and the square of the velocity fluctuation intensity σ_v^2

$$\varepsilon_a = \sigma_v^2 T_L.$$

Thus, the Lagrangian time scale is proportional to the Eulerian spatial scale L_E and time scale T_E:

$$T_L = \frac{1}{1/T_E + 0.8\sigma_v/L_E},$$

and it may be inferred that the increase in ε_a is related, on the one hand, to an increase in the Eulerian macroscales. However, the noted growth of ε_a with the gas injection rate would not be as large if the reason for that growth were merely an increase of the scales. The growth of ε_a in the presence of the gaseous phase can be calculated from the relation

$$\frac{\varepsilon_a' + a}{\varepsilon_a + a} = \frac{\left(\dfrac{\partial t}{\partial y}\right)}{\left(\dfrac{\partial t}{\partial y}\right)'}.$$

Here ε_a and ε_a' are the turbulent thermal transport coefficients in single- and two-phase flows, respectively. The ratios $(\varepsilon_a' + a)/(\varepsilon_a + a)$ calculated from the measured spatial scales and temperature fluctuation intensities turn out to be rather large and cannot be attributed merely to a growth of the Eulerian scales. Therefore, in two-phase flow there is a large velocity fluctuation intensity relative to single-phase flow for the same average flow velocities. The enhanced turbulent activity of the flow occurs, obviously, due to a reduction in the effective molecular viscosity of the gas–liquid mixture.

It can be shown that the temperature fluctuation intensity is inversely proportional to the variance of the velocity fluctuations. Using the relation $\overline{\partial t}/\partial y = \overline{v't'}/\varepsilon_a$ and assuming that the expression $\sigma_t = L_E(\partial t/\partial y)$ holds, we obtain

$$\sigma_t = \frac{q_T L_E}{C_p \gamma \sigma_v^2 T_{L,t}} \approx \frac{q_T L_E}{C_p \gamma \sigma_v^2 T_E}.$$

Consequently, the reduction in the temperature fluctuation intensity further attests to the increase in the flow turbulence.

NOTATION

r_0	is the inside radius of pipe;
y	is the distance from wall;
$Y = y/r_0$;	
q_T	is the turbulent heat flux density;
C_p	is the heat capacity;
γ	is the density;
$\overline{t}$	is the time-average temperature at a point in the flow;
σ_t	is the temperature fluctuation intensity;
$R(\tau)$	is the autocorrelation coefficient;
$R(\delta)$	is the space correlation coefficient;

T_E	is the Eulerian time macroscale;
$T_{L,\overline{t}}$	is the Lagrangian time macroscale of temperature fluctuations;
L_E	is the Eulerian spatial macroscale;
σ_v	is the velocity fluctuation intensity;
a	is the thermal diffusivity;
ε_a	is the turbulent thermal diffusivity;
ε_a'	is the turbulent thermal diffusivity in the presence of the gaseous phase;
$\overline{v't'}$	is the correlation moment of velocity and temperature fluctuations;
V_w	is the water volumetric flow rate;
V_g	is the gas volumetric flow rate;
Re_0	is the Reynolds number;
τ	is the time shift;
δ	is the displacement in space.

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