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Measurement of the Adiabatic Wall Temperature of a Flat Plate in a Supersonic Air-Droplet Flow

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Abstract—The results of the measurement of the surface temperature of a flat plate in a supersonic air-droplet flow are presented. The plate made of duralumin was mounted vertically in the working channel of an aerodynamic setup. The droplets of a liquid (distilled water) were pulverized into an air flow in a plenum chamber through centrifugal atomizers. The mass concentration of the liquid was about 0.36 and 0.27%, the mean droplet diameter according to Sauter was about 110 μm, and the freestream Mach number $M = 2.5$ and 3.0. The surface temperature was measured by an IR imager. The measured plate surface temperatures for the case of single-phase air flow (without droplets) were compared with those for the air-droplet flow at the same parameters (with respect to the air) in the plenum chamber. To intensify the droplet sedimentation on the plate a shock generator in the form of a wedge was mounted vertically ahead of the plate.

Keywords: supersonic air-droplet flow, disperse gas flows, adiabatic wall temperature

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There has been much research devoted to the interaction between two-phase (disperse) flows and bodies in the flow (see, for example, review [1]). The presence of an even small amount of admixture (fractions of one percent) in the main flow can lead to considerable variations of its parameters on the body surface. In this study, emphasis is placed on the effect of the water droplet admixture in a supersonic air flow on the surface temperature of the body in the flow.

It is well known that the greater the flow Mach number the greater the difference between its thermodynamic temperature T and the adiabatic stagnation temperature T_0^*. For example, at the sonic velocity of an air flow this difference $(T_0^* - T)/T_0^*$ is 17%, while at Mach 3 it amounts to 65%. In this case, the gas directly on the adiabatic surface, impermeable for the heat flux, takes a temperature T_{aw} different from both the freestream stagnation temperature and its thermodynamic temperature. To name this temperature, the Russian scientific literature uses several equivalent terms, such as adiabatic wall temperature, recovery temperature, own wall temperature, temperature of a thermally-insulated wall, and equilibrium wall temperature. In this study, we will call it the adiabatic wall temperature, as recommended in [2]. The adiabatic wall temperature is determined by the expression [3]

$$T_{aw} = T_0^*\left(1 + r\frac{\gamma - 1}{2}\mathrm{M}^2\right)\left(1 + \frac{\gamma - 1}{2}\mathrm{M}^2\right)^{-1} \approx \begin{cases} T_0^*, & \mathrm{M} \ll 1 \\ r \times T_0^*, & \mathrm{M} \gg 1 \end{cases} \tag{0.1}$$

where T_{aw} is the adiabatic wall temperature (in the units of K), T_0^* is the stagnation temperature in the main flow, M is the Mach number, γ is the adiabatic exponent of the gas, and r is temperature recovery coefficient. The parameter r depends on many factors but, as shown by many experimental and numerical investigations [3, 4], in turbulent, separationless, single-phase flow past a plate and bodies of revolution with smooth generators (cylinder or cone) at the Prandtl number $\mathrm{Pr} \approx 0.7$, $r = 0.89 \pm 0.01$.

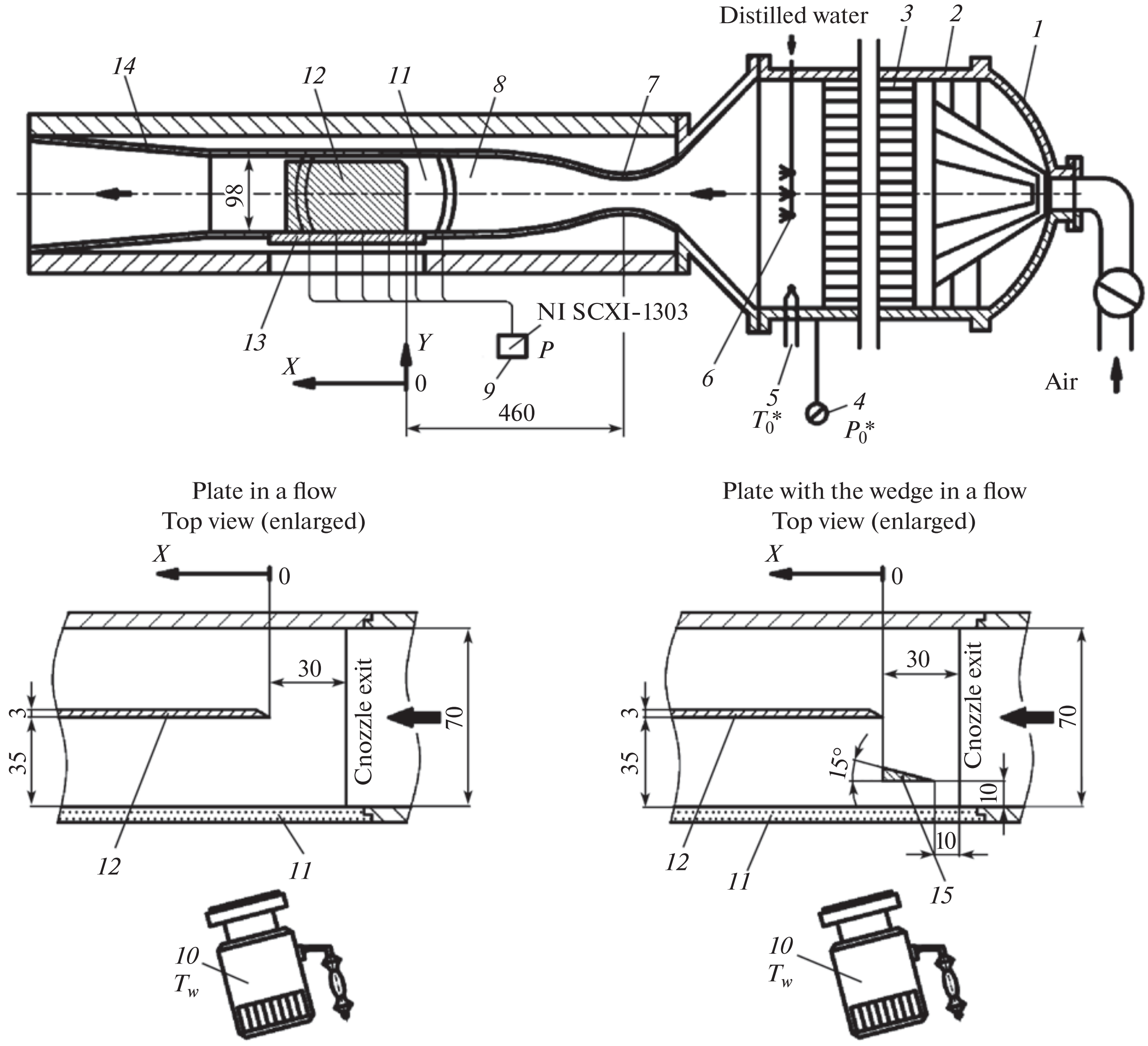

Fig. 1. Schematics of the supersonic experimental setup: *1*, plenum chamber; *2*, assembly of cones; *3*, honeycomb (wind straightener); *4* and *5*, transducers of stagnation pressure and temperature; *6*, set of centrifugal atomizers; *7*, plane adjustable nozzle; *8*, working channel; *9*, transducers of the static pressure and thermocouples; *10*, IR chamber; *11*, illuminator; *12*, experimental model; *13*, Plexiglas plate; *14*, diffuser; and *15*, wedge as the shock generator.

Then from Eq. (0.1) for the air (Pr ≈ 0.7) at M = 1 the quantity $(T_0^* - T_{aw})/T_0^* \approx 2\%$, while at Mach 3 it amounts to about 7%, that is, it is actually similar in value with T_0^* rather than T, and, therefore, is far from the minimum temperature in the flow past the body.

In many applied problems, such as heat protection, machine-free energy separation, etc., the reduction of the adiabatic temperature against the stagnation temperature lead to a considerable increase in the positive effect [5–11]. For example, this circumstance can be used for improving the effectiveness of the machine-free energy separation devices operating according to the scheme proposed in [5].

In [12, 13] it was experimentally shown that on expansion of a moist water vapor (vapor charged with water droplets with the moisture up to 4.5%) in a nozzle the temperature of the adiabatic nozzle wall decreases compared with the case of overheated vapor flow. In [12] the recovery coefficient took the values $r = 0.7$ in the moist vapor and $r = 0.9–0.8$ in the overheated vapor, depending on the initial overheating degree. In [13] it was shown that the adiabatic wall temperature depends on both the initial moisture content and the initial droplet dispersivity. At droplet dimensions $d > 70$ μm and the initial moisture content

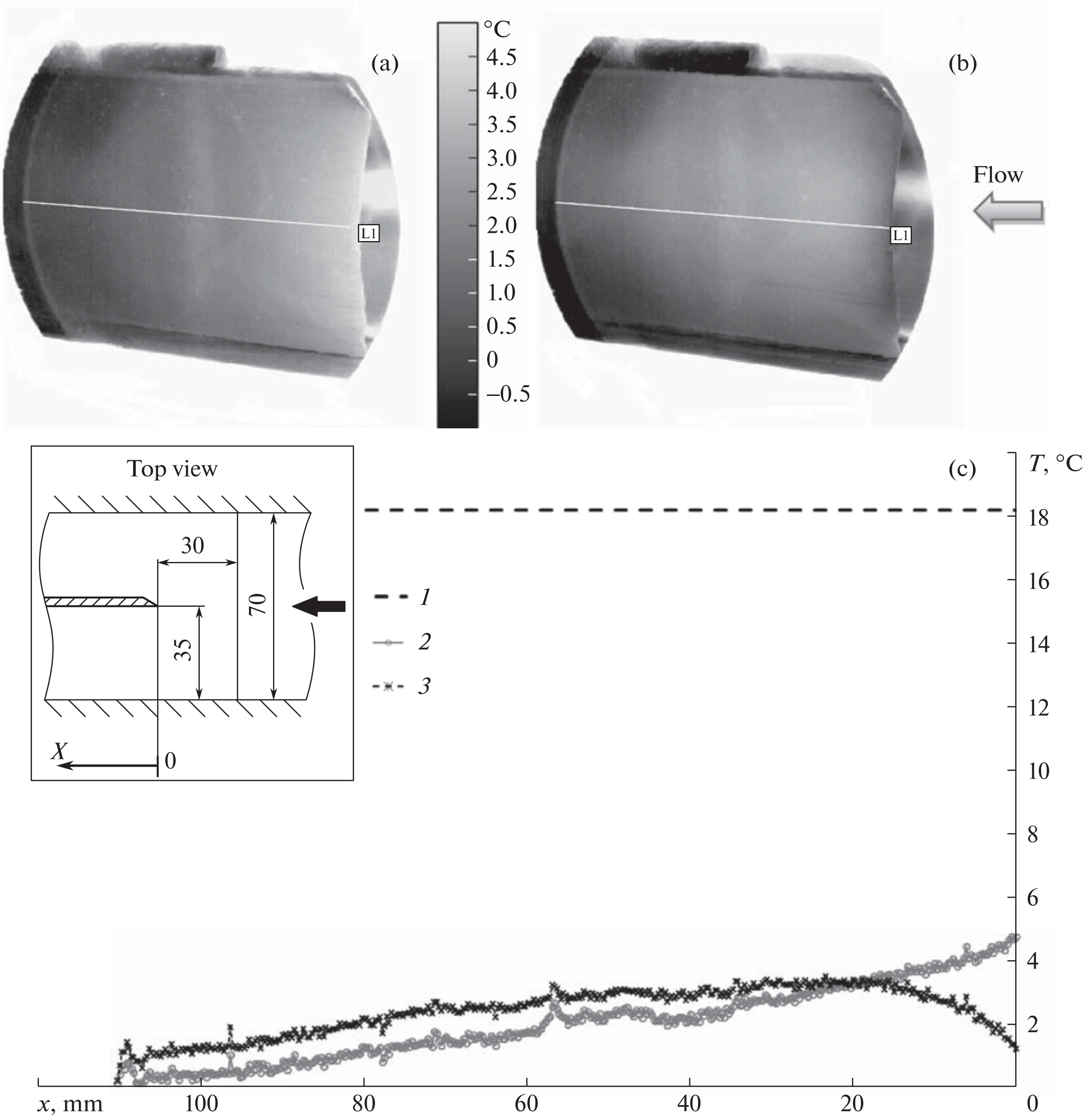

Fig. 2. Thermograms of the plate surface in air (a) and air-droplet (b) flows and distributions of the adiabatic wall temperature over the central area of the plate in the two flow regimes (c): $T_0^* = 18.3°C$, $M = 3.0$, and $m = 0.36\%$; *1*, stagnation temperature T_0^*; *2*, single-phase air flow; and *3*, air-droplet flow.

$m > 2\%$ the droplets precipitated on the wall forming a liquid film with a temperature same as the saturation temperature.

In [14–16] it was numerically shown that the presence of an even small (to 3%) droplet concentration in the main air flow can lead to a considerable reduction in the adiabatic wall temperature of a body in a flow.

In this study, the temperature of the adiabatic wall temperature of a flat plate in a supersonic single/two-phase flow is measured in the presence and absence of an incident shock.

1. METHOD OF INVESTIGATION

The investigations were performed on a supersonic AR-2 setup with closed test section and a plane adjustable supersonic nozzle (Fig. 1). The test section dimensions are as follows: the length is 450 mm,

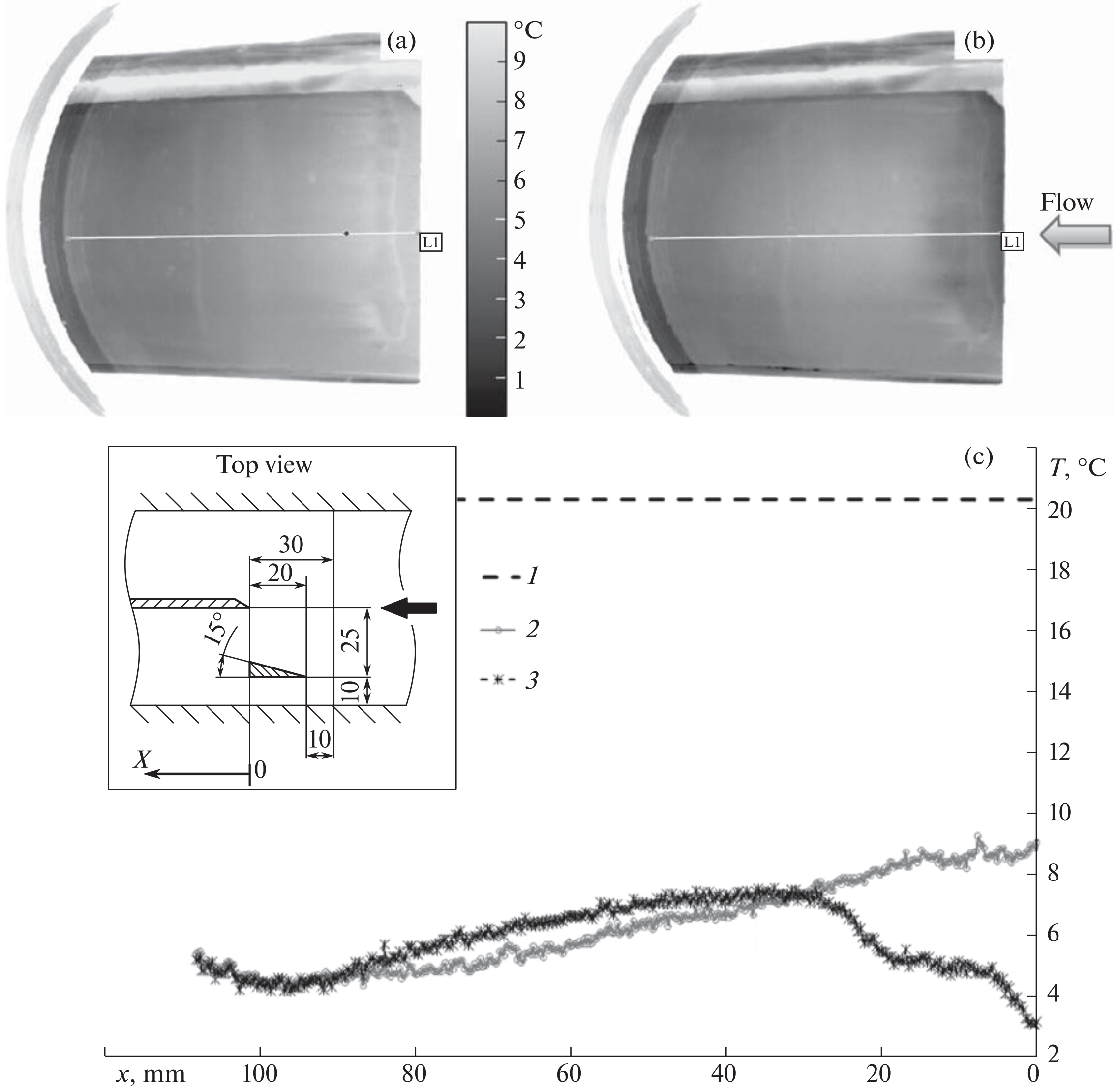

Fig. 3. Thermograms of the plate surface in air (a) and air-droplet (b) flows and distributions of the adiabatic wall temperature over the central area of the plate in the two flow regimes (c): $T_0^* = 20.5$°C, M = 3.0, and $m = 0.36\%$; *1*, stagnation temperature T_0^*; *2*, single-phase air flow; and *3*, air-droplet flow.

the width is 70 mm, and the height is 98 mm. A 87 mm-high, 3 mm-wide, and 170 mm-long plate made of duralumin was mounted vertically, along the central line of the working channel, at a distance of 30 mm from the nozzle exit.

The setup is equipped with both optical windows and an IR ZnSe illuminator which makes it possible to fix the flow shadow picture using the Toepler instrument and the temperatures of the lower and side surfaces of the working channel using an InfraTEC 8855 IR imager. Droplets were pulverized into the air flow in the plenum chamber through five centrifugal Lechler 220.185 atomizers with known characteristics (the size distribution of the diameter depending on the water pressure difference on an atomizer). The setup was also equipped with a system of the gas-droplet flow visualization consisting of a laser knife and photoinstrumentation, which makes it possible to qualitatively assess the flow structure.

In this study, the freestream Mach number at the nozzle exit was 2.5 and 3.0. The mass concentration of the water $m = 0.27$ and 0.36%, respectively. According to the characteristic presented by the manufacturer of the atomizers, the mean Sauter diameter (mean spatial-surface diameter of the particles) of the pulverized particles was 110 μm at the 300 kPa pressure difference on the atomizers. The temperatures of the lower channel wall and the side surface of the plate were measured. The measured temperature was

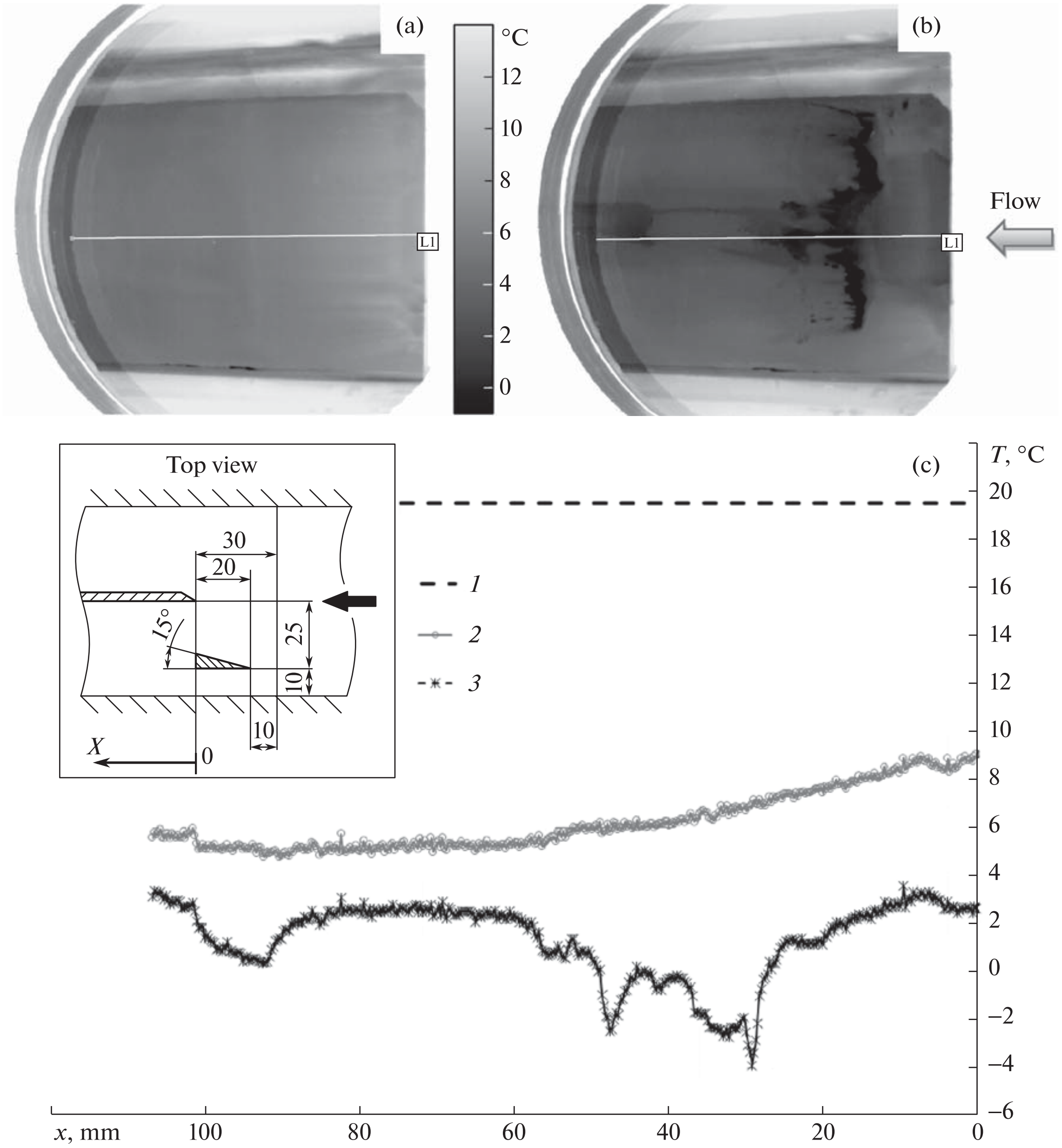

Fig. 4. Thermograms of the plate surface in air (a) and air-droplet (b) flows and distributions of the adiabatic wall temperature over the central area of the plate in the two flow regimes (c): $T_0^* = 19°C$, M = 2.5, and $m = 0.27\%$; *1*, stagnation temperature T_0^*; *2*, single-phase air flow; and *3*, air-droplet flow.

taken to be the adiabatic wall temperature. The results of the measurements for the single-phase air flow were compared with those for the air-droplet flow at the same parameters in the plenum chamber (with respect to air). The temperature of the pulverized droplets was similar in value with the air flow stagnation temperature (within the limits of 2°C). A set of experiments, in which a shock generator in the form of a wedge mounted vertically ahead of the plate was used to intensify the droplet sedimentation on the plate surface, was also conducted.

2. RESULTS

In Fig. 2 the thermograms of the surface of the plate in air (Fig. 2a) and air-droplet (Fig. 2b) flows are presented for $m = 0.36\%$. The Mach number at the nozzle exit M = 3.0. When droplets were added into the flow, the plate edge temperature reduced by 4°C and then restored to the values obtained in the case of the single-phase flow at a distance of 18 mm (Fig. 2c).

In the single-phase flow the location of the shock generator ahead of the plate (Fig. 3) at the same freestream Mach number (M = 3) has almost no effect on the nature of the temperature distribution over the plate surface. However, in the case of the air-droplet flow the plate edge temperature reduced by 6°, while the distance, at which the surface temperature restored to the values characteristic of the single-phase flow, increased by a factor of 1.5, up to 28 mm. The effect of the shock generator was more considerable in the case in which M = 2.5 and $m = 0.27\%$ (Fig. 4). In this case, there was ice fall-out in the central region of the plate (dark regions in Fig. 4b), which led to a local reduction in the surface temperature by 10–13°C (in Fig. 4c the temperature distribution in the central region of the plate is presented).

SUMMARY

The results of the measurements of the surface temperature of a flat plate in a supersonic flow are presented. Two flow regimes are investigated. The first regime corresponds to the single-phase flow of dry air, while in the second case it is the air-droplet flow consisting of a mixture of dry air and fine-disperse water droplets with the mean Sauter diameter of 110 μm. At the Mach number M = 3 and the mass concentration $m = 0.36\%$ the presence of the droplets leads to a small (to 4°C) reduction in the temperature of the leading edge of the plate. Then the temperature restored to the values obtained in the single-phase flow at a distance of 18 mm from the edge. Mounting the shock generator ahead of the plate enlarged the low-temperature area on the plane by a factor of 1.5. The greatest reduction in the plate surface temperature was achieved in the M = 2.5 regime, in the presence of the shock generator ahead of the plate. Due to an increase in the air flow rate the mass concentration of water diminished to $m = 0.27\%$. In this case, there was precipitation in the form of ice on the plate surface, which led to a local temperature reduction by 10–13°C compared with the casse of the single-phase flow past the plate.

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DECLARATION OF CONFLICTING INTERESTS

The Authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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