Experimental study of the shock wave influence on adiabatic wall temperature in a supersonic air-droplet flow

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Abstract. The results of an experimental study of the thermal parameters of a supersonic flow around a flat wall in the presence of finely divided water droplets are presented. The relative mass flow rate of the liquid (mass concentration) varied in the range 0.05-0.5%. Liquid (distilled water) was sprayed through centrifugal nozzles into the air flow in the prechamber of the supersonic wind tunnel. Next, the adiabatic wall temperature for the given flow conditions was measured with the use of infrared thermal imager. The input flow Mach number was 2.5, the Reynolds number based on the dynamic boundary layer length from the nozzle throat was at least $2 \cdot 10^7$ at the nozzle exit section. The research was performed at the experimental facilities of the Institute of Mechanics of Lomonosov Moscow State University.

1. Introduction

It is well known that the higher the speed of the gas flow, the more its thermodynamic temperature differs from its stagnation temperature. For example, with the sound velocity of the air flow, this difference is 17%, and with Mach 3 it is already 65%. Figure 1 shows the profiles of thermodynamic temperature and stagnation temperature in the boundary layer for flow around a flat wall [1]. If the wall is thermally insulated, then the temperature of the gas wall layer will be equal to the adiabatic wall temperature $T_{aw}$.

In the practice of engineering and scientific calculations, the adiabatic wall temperature $T_{aw}$ is determined through the temperature recovery factor $r$:

$$T_{aw} = T_0 \cdot \frac{1 + r \frac{\gamma - 1}{2} M^2}{1 + \frac{\gamma - 1}{2} M^2}$$

In the case of turbulent, continuous flow around the plate the temperature recovery factor is about 0.89±0.01 [2]. However, the wall can heat up ($r$ increases) or cool down ($r$ decreases) under the influence of a pressure gradient, complicating the surface shape and the presence of strong perturbations in the flow (shock waves, separated flows, phase transitions).

In many applied problems (thermal protection, machine-free energy separation, etc.), a decrease in the temperature of the heat-insulated surface relative to the stagnation temperature leads to a significant increase in the positive effect [3-5]. The question arises - is it possible to create such flow conditions under which the surface temperature of a thermally insulated wall would be close to the flow thermodynamic temperature - the minimum possible flow temperature.
The effect of reducing the temperature recovery factor and the corresponding decrease in the adiabatic wall temperature down to values even lower than the thermodynamic temperature for the subsonic flow across the cylinder (Eckert-Weise effect) is known [6-8]. The effect of adiabatic wall temperature reducing propagates downstream in the wake of the cylinder. For supersonic flows, a decrease in the adiabatic wall temperature is recorded for a flow around a cylindrical wall follows a circular rib, on a flat wall behind a rib or a step, on a conical surface behind various heads in the form of a sphere, cylinder, cone and disk [9-12]. In two-phase supersonic flows it was shown [13-15] that the presence of even a very small concentration of droplets in the main stream can lead to a significant decrease in the adiabatic wall temperature. Results in [16] show that liquid droplets in a supersonic flow can focus along the shock wave front which can contribute for the aim of precipitation of drops on the wall.

The aim of this work is an experimental study of wall cooling possibility due to supersonic flow around it by using the properties of gas-droplet flows with a low mass concentration of the liquid phase (up to one percent). In this case, the liquid phase practically does not affect the properties of the main gas flow, while the droplets themselves can be cooled to the flow thermodynamic temperature. By organizing the precipitation of chilled drops on the wall it is possible to achieve a decrease in the surface temperature.

2. Methodology

A series of experimental measurements of the cooling rate of a flat model streamlined by a supersonic air-droplet flow in the supersonic wind tunnel was carried out (Figure 2). The input flow Mach number was M=2.5. The relative mass flow rate of the liquid ranged from 0.05% to 0.5%. A model plate was made of duralumin 3 mm thick, which was installed in the central part of the channel along the flow direction. In order to deposit droplets on the wall, an experiment was performed with a shock wave generator in the form of a vertical wedge with a 15 degrees opening angle mounted in front of the model plate.
Figure 2. Scheme of the experimental facility: 1 - prechamber; 2 - assembly of cones; 3 - honeycomb; 4 - sensor for measuring stagnation pressure; 5 - thermocouple for measuring stagnation temperature; 6 - a set of water nozzles; 7 - working channel; 8 - flat adjustable supersonic nozzle; 9 - static pressure sensors; 10 - infrared thermal imager; 11 - illuminator; 12 - experimental model; 13 - plexiglass bottom wall; 14 - diffuser

The supersonic wind tunnel is equipped with a closed working part and a flat adjustable supersonic nozzle [17, 18]. The working channel was 450 mm length, 70 mm width and 98 mm height. The measurements were carried out on the surface of the duralumin plate with the InfraTEC 8800 thermal imager through a ZnSe illuminator placed on the side wall the working channel. Also, using a laser knife and photographic equipment, the distribution of droplets was visualized in the transverse and longitudinal sections of the channel.

At the initial instant of time, the stagnation temperature of dry air and the stagnation pressure in the prechamber were $T_0=294$ K and $P_0=0.6$ MPa, respectively. Water was supplied at an excess pressure of 200 to 1000 kPa, which was maintained constant for about 2 minutes.

Liquid (distilled water) was sprayed into the air flow in the prechamber through the Lechler centrifugal nozzles with a spray cone-shaped torch. Spraying was carried out through 5 nozzles located around the axis of the prechamber [19]. With pressure drops from 200 to 1000 kPa realized in the experiment, the Sauter diameter of the droplets formed varied from 60 to 100 μm.

3. Results and discussion

At relative water flow rates of more than 0.2-0.3% the unsteadiness of the air-droplet flow increased substantially, namely, the frequency of the appearance of fluid clots in the flow increased. The presence of fluid in the flow was visible with a naked eye. Visualization of the flow pattern with a laser knife (Figure 3, left) showed that after passing through a supersonic nozzle, most of the droplets are concentrated near the channel axis in the form of a spot, the shape and dimensions of which depend on both the initial mass concentration of the liquid and the initial Mach number of the flow.

Using a thermal imager made it possible to record the effect of lowering the temperature of the lower wall of the channel on which the model plate was fixed by up to 15 degrees in the air-droplet flow regime (Figure 3, right). During the experiment without a thermal imager, the side infrared ZnSe illuminator was replaced with an illuminator made of transparent optical glass. In this case, it was possible to observe the appearance of ice growths on the lower wall adjacent to the model plate (Figure 3, right).
At the same time the value of the adiabatic wall temperature of the model plate changed insignificantly in the range of all the investigated pressure drops in the water nozzles from 200 to 1000 kPa, which means that when the water relative mass flow rate changes from 0.05 to 0.5%. Visualization with a laser knife showed that the plate is located directly in the area of distribution of the droplet flow.

The reason for almost constant adiabatic wall temperature of the model plate without the shock wave generator may be the deviation of the streamlines of the air-droplet flow along the front of the head shock wave on the nose of the model plate. As a result, the droplets do not fall into the boundary layer formed on the plate, but instead repel from it, following the front of the shock wave.

In order to focus the droplets in the direction of the boundary layer developing on the plate, an experimental study was conducted with a shock wave generator installed in front of the plate. In this case areas with a decrease in temperature to 8-10 degrees were already visible in the central part of the plate (Figure 5). Visually, formation of ice growths was also observed in this area. The streamline pattern reconstructed using oil-paint visualization showed that the temperature decrease region is located behind the falling shock wave from the wedge.

Placing the shock wave generator in front of the plate led to a most significant effect in the mode $M = 2.5$ and $m = 0.27\%$ (Figures 5, 6). In this case, ice fell out in the central region of the plate (dark areas in Figure 5), which led to a local decrease in the surface temperature by 10-13 C (Figure 6 shows the temperature distribution over the center of the plate).
Figure 6. Distribution of the adiabatic wall temperature along the center of the plate for two flow regimes: $T_0 = 19 \, ^\circ C$, $M = 2.5$, $m = 0.27\%$; 1 - stagnation temperature $T_0$, 2 – single-phase air flow, 3 - air-droplet flow.

4. Conclusions
A series of experimental measurements of the supersonic flow adiabatic wall temperature of a flat plate was carried out. Two flow patterns were investigated. The first is a single-phase flow of dry air, the second is an air-droplet flow consisting of a mixture of dry air and finely divided water droplets. The presence of droplets in the flow at certain operating parameters (water concentration, Mach number, presence of a shock wave generator) led to the formation of ice growths on a streamlined surface with an adiabatic wall temperature reduced by 10-15 degrees. Placing the shock wave generator in front of the plate led to a more significant decrease in the local surface temperature.

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