Measurement of the adiabatic wall temperature in a supersonic air-drop flow

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Abstract. The results of the adiabatic wall temperature measurements of a flat surface placed in a supersonic flow with Mach number $M=2.95$ are presented. Two flow regimes were investigated. The first is a single-phase flow of dry air, the second is an air-drop stream consisting of a mixture of dry air and finely dispersed water droplets. The presence of droplets in the flow led to the formation of ice sheets on the measured surface, which in turn became the source of shock waves, which caused a strong non-uniformity in the variation of the static pressure and temperature on the measured surface. At this stage, the first data on the rate of cooling of the surface of the adiabatic plate with two flow regimes were obtained.

1. Introduction
It is well known that the higher the velocity of the gas flow, the greater its thermodynamic temperature $T$ differs from the stagnation temperature $T_0^*$. For example, at the sound velocity of the air flow, this difference $(T_0^*-T)/T_0^*$ is 17%, and at the Mach number 3 it is 65%. However, the gas directly on the surface of an adiabatic (impermeable to heat flow) flat plate placed in a high-speed flow takes a temperature $T_{aw}$ different from both the stagnation temperature of the high-speed flow and its thermodynamic temperature. For example, for air at sound velocity this difference $(T_0^*-T_{aw})/T_0^*$ is 2%, and at Mach number 3 it is 7%, i.e. it is actually very close to the stagnation temperature and it is called an adiabatic wall temperature.

In many applications (thermal protection [1], machine-free energy separation [2,3], etc.), a decrease in the adiabatic wall temperature relative to the stagnation temperature leads to a significant increase in the positive effect (reduces the maximum temperature of aerodynamic heating; increases the specific heat fluxes). The question arises whether it is possible to create conditions in the flow under which the adiabatic wall temperature would be close to the thermodynamic temperature of the flow – the minimum possible temperature of the flow. Probably, the solution of this problem is possible through the use of the properties of gas-drop flows with a low mass concentration (up to percent by weight) of the liquid phase. In this case, the liquid phase does not affect the properties of the carrier gas flow, while the droplets themselves can be cooled to the thermodynamic temperature of the flow. By organizing the precipitation of cooled drops on the wall, it is possible to achieve a significant decrease in the temperature of its surface.

In the scientific literature, the authors found only one experimental [4] and two numerical [5,6] works devoted to this issue. In [4], it was shown experimentally that the temperature of the adiabatic wall placed in a supersonic flow of wet steam can be equal to the thermodynamic temperature of the flow if
there were water droplets of a certain size and concentration in the wet steam. In [5,6] in the framework of a two-continuum model of a compressible gas-droplet boundary layer in a supersonic two-phase laminar flow on a flat wall, mass and energy flows of the dispersed phase on the surface were calculated. It was shown that even the presence of a very small mass concentration of drops in the mean flow can lead to a significant decrease in the adiabatic wall temperature. In this paper, the initial temperature of the droplets was assumed to be equal to the thermodynamic temperature of the supersonic flow.

This paper presents a description of the experimental equipment, measurement techniques and the first results needed to determine the adiabatic wall temperature in the air-drop flow.

2. Description of the experimental setup and the measurement technique

Experimental studies were conducted at the supersonic aerodynamic facility AR-2 (figure 1). The test section of the AR-2 has a rectangular cross-section with dimensions of 70×98 mm.

![Figure 1. Scheme of the supersonic aerodynamic facility AR-2.](image)

1 - settling chamber; 2 - assembly of cones; 3 - honeycomb; 4 - probe measuring the stagnation pressure; 5 - thermocouple for measuring the stagnation temperature; 6 - water nozzle; 7 - test section; 8 - flat adjustable nozzle; 9 - static pressure sensors and thermocouples; 10 - IR camera (thermal imager); 11 - infrared illuminator; 12 - optical glass illuminator; 13 - probe for measuring the stagnation temperature in the boundary layer; 14 - adiabatic wall; 15 - diffuser.

Illuminators with optical glasses (12) are mounted on its side walls to visualize the flow pattern by the shadow method using the device IAB-451. On the upper wall of the test section there was an illuminator made of ZnSe (11) polycrystals. This material is transparent in the infrared region of the spectrum, which made it possible to use the FLIR ThermaCAM SC-3000 (10) IR camera for contactless determination of the model surface temperature.

The experimental model (14) is a plate made of plexiglas, which was installed on the lower wall of the test section of the aerodynamic facility parallel to the main flow, directly adjacent to the nozzle section. The width of the model equal to the width of the test section is 70 mm, length is 200 mm. The material of the model has a low coefficient of thermal conductivity (λ = 0.19 W/(mK)), which allowed to consider it adiabatic.

Along the central line of the model the static pressure orifices were made. The stagnation pressure and temperature of the flow were measured in the settling chamber (1). On the model surface, 15 thermocouples were also installed along the center line to record the value and rate of change of the model surface temperature.
Data from all sensors were transmitted into the thermocouple and pressure sensor connector blocks NI SCXI-1303 and then through amplifiers SCXI-1102 (for thermocouples) and SCXI-1102B (for pressure sensors) were transmitted into the analog-to-digital converter NI PCI-6220. The program for obtaining and processing experimental data was written in LabVIEW and designed in the form of virtual devices on the PC monitor screen.

A water nozzle was placed in the upper wall of the settling chamber at a distance of 300 mm from the beginning of the narrowing zone. The average size of water droplets in the spray created by the nozzle (according to the manufacturer) is about 80 microns. The supply of distilled water to the nozzle was carried out through a separate system consisting of a tank with distilled water under pressure (the pressure of the water in the tank was pumped and maintained at a given level by a pneumatic system), a flowmeter device and tubes. Water droplets were sprayed through the nozzle in the settling chamber, where they were mixed with dry air.

Experimental studies were carried out as follows. After starting the aerodynamic facility, the surface of the model began to cool. Its temperature varied from the initial – equal to the ambient temperature, to a certain value depending on the time of operation and in the limit approaching to the value of the adiabatic wall temperature for given \( T_{0}^{*} \) and \( M \). Next, the adiabatic wall temperature and the heat transfer coefficient for these flow conditions are determined by the surface cooling rate using the technique described in [7].

At the initial time, the dry air stagnation temperature and stagnation pressure in the settling chamber were \( T_{0}^{*} = 294 \) K and \( P_{0}^{*} = 0.6 \) MPa, respectively. During the experiment, the stagnation pressure remained almost constant, and the stagnation temperature by the time of the water supply was reduced to 292 K (the aerodynamic facility is not equipped with an air heating system).

The Mach number upstream of the model was 2.95, mass air flow was 2.2 kg/s. The Reynolds number is defined by the distance from the throat of the nozzle (430 mm), was about \( 1.6 \times 10^7 \), which indicates a turbulent flow regime. The model was located directly behind the nozzle edge.

Water supply was carried out at a pressure of 1.59 MPa, which was maintained constant for about 2 minutes. The water mass flow rate was 0.014 kg/s or 0.65% of the air mass flow rate.

Uncertainty of measurement of basic parameters was estimated for 95% confidence interval [8]: ±0.25% for static pressure, ±1.5% for stagnation pressure in the settling chamber, ±0.36% for wall temperature (measured by thermocouples), ±1.2% for Mach number, ±2.7% for Reynolds number.

3. Results and discussion

Figure 2 shows the static pressure profiles measured along the surface of the model at the supersonic air flow and after the water supply through the nozzle in the settling chamber. In the case of air flow without droplets, there is some increase in static pressure caused by an increase in the thickness of the boundary layer along the model (the height of channel is constant). The Mach number determined from measured pressure ratios: stagnation pressure in the settling chamber and static on the surface of the plate using the isentropic dependence varied from 2.95 to 2.8. Water injection has resulted in nonuniformity in the profile of the static pressure. The reasons of this will be discussed below.

Figure 3 shows the cooling rate of the model surface measured by thermocouples located at the points of the model surface with coordinates \( x / L = 0.18; 0.26; 0.32; 0.44 \). It should be noted that the temperature of the model surface during the operation time did not reach its equilibrium value, i.e. we did not enter the steady thermal regime. The effect of water droplets in the supersonic flow on the adiabatic wall temperature and the heat transfer coefficient can be estimated only after processing the experimentally registered cooling rate. At this stage, it can be noted that the presence of water droplets in the flow was observed with the naked eye through the optical windows on the side walls of the test section. Also, the drops led to an increase in the non-uniformity in the temperature distribution over the model surface, which is clearly seen in the thermogram shown in figure 4b.
Starting from the junction of the lower wall of the supersonic nozzle and the model, moisture condensation from the supersonic air-droplet flow occurred, which accumulated in the form of ice growths on the model surface (figure 5 and dark "tails" in figure 4b). These growths led to the occurrence of shock waves, which caused irregularities in the distribution of static pressure.
4. Summary and conclusions

Experimental studies have been conducted and the first results on the effect of droplet admixture on the cooling rate of the adiabatic surface placed in a supersonic air-droplet flow have been obtained. Two modes of flow around a flat adiabatic surface were investigated: dry air flow and air-droplet flow (a mixture of dry air and water droplets). The conditions of the experiments were similar. The Mach number on the nozzle section in all runs was $M = 2.95$. The relative mass flow rate of water was 0.65%. The initial stagnation temperature of the flow was 294 K. The air-drop mixture was created in the settling chamber by spraying water with a centrifugal nozzle (the average droplet size was about 80 µm). The water temperature was close to the dry air stagnation temperature. The following results were obtained.

The presence of droplet admixture in the flow could be observed with the naked eye. At the junction of the nozzle and the model, as well as at the junction of the side windows, the solid phase (ice) deposition from the supersonic gas-droplet flow was observed. The presence of ice on the surface of the plate led to disturbances observed in the shadow device, which caused a more significant deceleration of the flow at the length of the plate compared to the single-phase flow. It was obvious that the main part of the liquid phase moved with the flow and had no effect on the surface temperature. The surface temperature distribution in the case of air-droplet flow was more non-uniform in comparison with the single-phase flow.

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