The effect of the initial swirl of the supersonic flow of humid air on the adiabatic wall temperature

A G Zditovets, N A Kiselev, S S Popovich, Yu A Vinogradov
Lomonosov Moscow State University, Institute of Mechanics, 119192 Russia
Moscow, Michurinskiy prosp., 1
zditovets@mail.ru

Abstract. The paper presents the results of measuring the adiabatic wall temperature of an axisymmetric channel during acceleration of the moist air flow in it to supersonic speed. The initial swirl was imparted to the flow (swirling parameter $S = 0.5, 1.0, 2.5$). The relative initial humidity (RH) of the flow varied in the range of $10 \div 90\%$. When the flow was accelerated to supersonic speeds, part of the moisture condensed, which influenced the wall temperature. It is shown experimentally that with an increase in the initial moisture content of the flow to certain values, the distribution of the wall temperature for a flow without initial swirl ($S = 0$) and with swirl with $S = 0.5, 1.0$ practically coincide. However, from a certain value of RH, the wall temperature in the case of a swirling flow decreases in comparison with a flow without swirling. The maximum decrease in the wall temperature was achieved at RH = 90\%. An increase in the initial swirl to $S = 2.5$ led to a greater decrease in the wall temperature, while the mass air flow through the channel decreased by 26\% at an identical pressure drop.

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.
Obviously, the larger the droplet size, the higher the mismatch between the velocities and temperatures of the liquid and gaseous phases. As indicated in [4], the velocity and temperature of the liquid and gaseous phases are practically equal if the droplet diameter is $d < 0.5 \mu m$. One of the ways to obtain droplets of such small sizes is the condensation of the components of the gas mixture (for example, water vapor from humid air) during expansion in a supersonic nozzle [5]. The diameter of the droplets formed in the condensation shock lies in the range 0.01–0.1 $\mu m$. In this case, due to the release of latent heat, the stagnation temperature of the flow after the condensation shock increases, and the Mach number decreases, these should lead to an increase in the value of the adiabatic wall temperature. On the other hand, the penetration of “cold” drops into the “hot” boundary layer should reduce the $T_{aw}$ value. In this case, the initial swirling of the flow should help to remove droplets from the flow and, accordingly, reduce the value of $T_{aw}$.

The purpose of this work is to experimentally investigate the effect of initial swirl on the value of the adiabatic wall temperature in a stream of moist air.

2. Description of the experimental setup and the measurement technique

The test section of the experimental facility is shown on figure 1. The studies were carried out in an axisymmetric channel made of brass (figure 1). A swirling blade device was placed between the settling chamber and the channel, in a removable section. Then there was a section with a smooth narrowing from 14 mm to 7 mm, after which a cylindrical section of a circular cross-section (diameter 7 mm) with a length of 35 mm began. The outlet section of which is taken as the "throat" of the channel and the origin of the longitudinal coordinate. Behind the throat, there was a conical section 150 mm long with an angle of 1.1 ° and, then, a cylindrical section of circular cross-section 150 mm long and 10 mm in diameter. At the outlet of the channel there was a diffuser and a receiver connected to the atmosphere (not shown in figure 1). Static pressure taps were located along the entire length of the channel with different densities. The temperature of the outer surface of the working channel $T_w$ was recorded with an InfraTEC 8855 thermal imager. To reduce the effect of background radiation, the outer surface of the channel was covered with a thin layer of matte black paint.

The gas flow (dry air, humid air) entered the channel from the settling chamber, which contained receivers for total pressure $P_0^*$, stagnation temperature $T_0^*$, and a flow relative humidity sensor RH. The mass flow rate of “dry” air $\dot{G}_d$ (before mixing with superheated water vapor) was measured by a Coriolis mass meter with an uncertainty of 0.5% of the measured value.

Moist air was obtained by adding superheated water vapor to the "dry" air in a special mixing chamber located in front of the settling chamber. Air after the compressor and before mixing with superheated steam is conventionally considered "dry". The change in the RH value was achieved by

![Diagram of experimental facility](image)
increasing the consumption of superheated steam. In this case, in all investigated modes, the total pressure of humid air and the stagnation temperature in the prechamber were maintained constant, and

\[ P_\omega = 300 \pm 3 \text{kPa} \quad \text{and} \quad T_\omega = 46.7 \pm 0.3 \text{ ºC}, \]

respectively. In this study, the initial relative humidity of "dry" air at the above \(P_\omega\) and \(T_\omega\) was \(\text{RH} \approx 8-9\%\). The ambient temperature was 26÷28 ºC.

For calculating the distribution of the mean-mass Mach number in the case of "dry" air, an expression for calculation the mass flow rate of gas through a cross-section with a diameter \(d\) was used:

\[
G_a = \frac{\pi \cdot d}{4} \cdot M \cdot \left[ \frac{2}{\gamma + 1} \cdot (1 + \frac{\gamma - 1}{2} \cdot M^2)^{\frac{\gamma + 1}{\gamma - 1}} \cdot \left( \frac{\gamma - 1}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}} \right] \quad (1)
\]

where \(\gamma\) and \(R\) is the specific heat ratio of the gas and the gas constant of air, respectively. The distribution of \(M(x)\) was determined from expression (1) using the measured values of \(p_{st}(x)\), \(G_a\) and the known distribution \(d(x)\).

It should be noted that expression (1) in the case of a flow with an initial swirl \(S \neq 0\) was used only to estimate the mean-mass Mach number, since in this case the distribution of static pressure in the cross section cannot be assumed to be uniform.

Also, to estimate the Mach number in the core of the flow for a flow of "dry" air without swirling \((S = 0)\), the well-known expression for the isentropic flow was used:

\[
M_{is} = \frac{2}{\gamma - 1} \cdot \left[ \left( \frac{p_{st}}{P_0^\gamma} \right)^{\frac{1}{\gamma - 1}} - 1 \right] \quad (2)
\]

Obviously, the value of the Mach number determined in this way will be greater than the real value on the channel axis, since expression (2) does not take into account the total pressure loss along the channel length caused by friction. However, the \(M_{is}\) value calculated by expression (2) can be considered as the “upper” estimate of the Mach number on the channel axis.

In the experiments, blade swirling devices with various swirling parameters \(S = 0.5; 1.0; 2.5\) were used. The devices were made from PLA plastic by 3D printing. The blades were profiled in such a way as to ensure the law of swirl - "solid body" - the circumferential speed is proportional to the radius. In this case, the swirling parameter of the flow is related to the blade angle \(\varphi\) by the following relationship [6]:

\[
S = \frac{2}{3} \cdot \left( \frac{1 - (d_h/d)^3}{1 - (d_h/d)^2} \right) \cdot \tan \varphi,
\]

where \(d_h = 7\) mm is the diameter of the hub and \(d = 14\) mm is the outlet diameter of the blade device.

3. Results and discussion

At the first stage, the swirling device was not installed, and section 2 was absent. This mode is denoted in the figures \(S = 0\). For different values of the initial relative humidity, the distributions of static pressure \(p_{st}(x)\), and wall temperature \(T_w(x)\) were recorded. As can be seen from figure 2a, the static pressure distribution in the mode with the lowest RH ("dry" air) value is smooth. Figure 3a shows the results of calculating the mean-mass Mach number according to the equation (1) and the distribution of the Mach number according to the isentropic dependence (equation (2)). Throughout the channel, the flow velocity is supersonic. The flow is accelerated to the end of the conical section \((x = 150\) mm) and then decelerated in the cylindrical section. The change in the wall temperature is similar to the change in static pressure - in the area of flow acceleration, the temperature decreases, in the area of deceleration, it increases. However, the transition from decline to growth occurs smoothly, probably due to the influence of the thermal conductivity of the channel. An increase in the initial relative humidity up to 60\% leads to the appearance of pronounced pressure surges - condensation shocks.
Figure 2. Distribution of static pressure (a) and adiabatic wall temperature (b) at different values of the initial relative humidity RH in a duct without a swirling device (S = 0). $P^* = 300 \pm 3$ kPa; $T^*_0 = 46.7 \pm 0.3$ °C

When the flow passes through the condensation shock, its parameters change due to heat release: the total pressure and the Mach number decrease, the static pressure, static temperature, and also the stagnation temperature increase. In the case of a single-phase flow, such a change in the flow parameters should lead to an increase in the adiabatic wall temperature. In a two-phase flow, the movement of droplets in the transverse direction can cause a deviation in the $T_{aw}$ distribution that follows from the one-dimensional one-phase flow.

Figure 3. a - distribution of the mean mass Mach number $M$ (equation (1)) and the Mach number on the channel axis $M_0$ (equation (2)) in the channel without swirling $S = 0$ in the “dry” air mode (RH = 10.6%); b - distribution of the mean mass Mach number (equation (1)) depending on the swirl parameter in the “dry” air mode.

Figure 2b shows that with an increase in the RH value up to 50%, the wall temperature increases throughout the channel relative to the values obtained in "dry" air. At RH 60.3%, the character of the change in $T_{aw}$ practically coincides with the regime at RH = 50.2%. In the modes RH=70 ÷ 90%, the
distribution of $p_{st}(x)$ has a smooth character throughout the channel, while the absolute value of $p_{st}(x)$ is slightly $(1 \div 4 \text{ kPa})$ higher than in the regime with RH = 60%. At the same time, at modes RH = 70 ÷ 80%, the value of $T_{aw}$ insignificantly ($\approx 2^\circ \text{C}$) increases in the entire region as compared to the regime RH = 60%. In the RH = 90% mode, there was a slight deviation in the $T_{aw}$ distribution, relative to the value observed in the RH = 70 ÷ 80% modes, which consisted in a decrease in $T_{aw}$, starting from the middle of the conical section, to the $T_{aw}$ values achieved in the RH = 40% mode. It should be noted that starting from the mode RH = 70.4%, it is impossible to determine the position of the condensation area only by the distribution of static pressure.

Figure 4 a and b shows the distribution of $p_{st}$ and $T_{aw}$ depending on RH in the presence of an initial swirl in the channel (swirling parameter $S = 2.5$). The presence of swirling significantly changed the nature of the distribution of static pressure: firstly, an increase in the total pressure loss led to the displacement of the shock wave inside the channel (figure 3b shows the distribution of the mean-mass Mach number for the case of "dry" air at $S = 0; 0.5; 1.0; 2.5$); second, the pressure distribution before the shock wave is smooth, i.e. there is no pressure surges which show the presence of a condensation shock in a stream without swirling; third, an increase in the initial RH of the flow has practically no effect on the magnitude and nature of the $p_{st}$ distribution in the supersonic region and insignificantly (by 10 mm) shifts the region where the shock occurs downstream. Also, in the channel with an initial swirling parameter $S = 2.5$, the effect of the initial relative humidity on the wall temperature turned out to be opposite to that observed in the channel without swirling. In this case, an increase in RH up to 70% leads to a decrease in the wall temperature along the entire length of the channel. At RH = 70 ÷ 90%, the wall temperature distribution practically does not change.

Figure 5 shows the distributions of $p_{st}$ and $T_{aw}$ at nearly equal RH values for different values of the swirl parameter $S$. The following trends can be noted:

- the presence of swirling leads to the displacement of the shock wave into the channel;
- with an increase in the initial swirling parameter, the shock wave moves upstream;

![Figure 4](image-url)
• with an increase in the initial relative humidity up to 30%, the shock wave in the flow with swirling moves downstream. A further increase in RH does not affect the location of the shock;
• in channels with swirl, there are no pronounced pressure surges corresponding to condensation shocks;
• in the "dry" mode in the region $M > 1$, the $T_{aw}$ distributions practically coincide for all values of $S$;
• with an increase in RH up to 50%, the value and distribution of $T_{aw}$ for channels with $S = 0; 0.5; 1.0$ are practically the same, starting from RH $\approx 70\%$, the wall temperature in a channel with swirl becomes lower than in a channel without swirling in the entire region at $(x > 0)$;
• at $S = 2.5$, an increase in RH leads both to a decrease in the minimum value of $T_{aw}$ and to the propagation of a region of low (in comparison with the channel with $S = 0$) temperatures;
• in channels with a swirling parameter $S = 0.5; 1.0$, the value of $T_{aw}$ decreases continuously, starting from RH $\approx 50\%$, while in a channel with $S = 2.5$, the distribution of $T_{aw}$ at RH $> 70\%$ is practically constant.

\[ RH \approx 9\% \text{ ("dry" air)} \]

\[ RH \approx 30\% \]
Figure. 5. Influence of the swirling parameter $S$ on the distribution of static pressure (left column) and adiabatic wall temperature (right column) at different values of the initial relative humidity RH. $P_0^* = 300 \pm 3$ kPa; $T_0^* = 46.7 \pm 0.3$ °C.

4. Summary
Experimental studies on the influence of the initial swirling parameter $S$ on the adiabatic wall temperature at various values of the initial relative humidity RH showed that the presence of swirl in a "dry" air flow practically does not affect the value and nature of the $T_{aw}$ distribution in the region...
where flow has a supersonic speed. In this case, the effect of swirling is reduced to an increase in the total pressure loss and a decrease in the region of supersonic flow realized at a given initial pressure drop. With an increase in the value of RH, the effect of swirling is the greater, the greater the initial swirling parameter. Beginning with RH = 50%, the wall temperature in the flow with swirl is lower than without swirling for all values of S. Probably, this is the result of moisture condensation in the flow core and the penetration of low-temperature droplets into the near-wall layers with a higher temperature.

5. References
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