Experimental research of supersonic flow heat transfer in the wake of a backward-facing step

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Abstract. The results of an experimental study of heat transfer for a supersonic flow behind a backward-facing step are presented. Input flow Mach number was 2.2, Reynolds number was over 20 million when calculated with the use of the dynamic boundary layer length from the critical section to the exit section of the nozzle. The height of the step ranged from 8 to 14 mm. The thickness of dynamic boundary layer for plane model flow was about 6 mm in the region of nozzle exit section. The heat transfer coefficient and adiabatic wall temperature for the wake flow behind the step have been analysed in comparison with the plane model flow. The experiment was made with the use of chromel-kopel thermocouples with thermal compensation of cold junction, stagnation and static pressure meters, NI LabView powered programs of experimental automation. The graphs of the wall temperature, stagnation flow temperature, adiabatic wall temperature, the stagnation and static pressure, the distribution of the temperature recovery coefficient and the relative Stanton number along the model length are presented.

1. Introduction

Due to viscous dissipation in the boundary layer of a supersonic compressible gas flow the total temperature redistribution takes place. As a result, the temperature in the inner part of the boundary layer is lower, while temperature in the outer part is higher than the rate in the main flow [1, 2]. If there is no heat transfer through the wall, the total temperature of the near-wall gas layer takes the value of the adiabatic wall temperature.

Heat transfer data, as a rule, are presented in the form of a heat transfer coefficient, which in the general case is determined by the ratio of the specific heat flux into the wall to the temperature difference between the instantaneous temperature of the streamlined wall and a certain determining temperature in the flow [3, 4]:

\[ h = \frac{q_w}{T_{aw} - T_w} \]

The determining temperature may be the thermodynamic temperature in the flow, the stagnation temperature, the initial temperature (at the entrance to the channel with heat sources or sinks), or the
adiabatic wall temperature. For high-speed flows the adiabatic wall temperature is applied as determining one which guarantees the accuracy of transferring the data obtained on wind tunnels to the actual operating conditions of the designed machine.

![Temperature profile in the thermal boundary layer for a supersonic compressible gas flow around a plane surface.](image)

**Figure 1.** Temperature profile in the thermal boundary layer for a supersonic compressible gas flow around a plane surface.

The ratio of the heat transfer intensity to the total potential heat transfer of the gas flow is determined by the Stanton number [4, 5]. The heat transfer data presented in the form of this dimensionless heat-transfer criterion are less sensitive to changes in the flow velocity as well as to changes in the wall temperature than the common heat transfer coefficient $h$:

$$\text{St} = \frac{q_w}{\rho_w u_w C_p (T_{aw} - T_w)}$$

Determination of the Stanton number using the above relation faces the problem of the adiabatic wall temperature calculation. As usual for engineering applications this value is calculated with the use of the temperature recovery factor $r$, the stagnation temperature of the flow $T_0$ and the input flow Mach number $M$:

$$T_{aw} = r \cdot T_0$$

Different experimental researches for gas flows [4, 5] have demonstrated that for a developed turbulent supersonic flow around a plane surface the temperature recovery factor appears to lie in the range 0.875 to 0.895. There is an interesting Eckert-Weise effect of temperature recovery factor decreasing and the corresponding adiabatic wall temperature reducing down to the meanings lower than the static temperature for flow with subsonic velocity across the cylinder [6-8]. It appears that the effect of temperature reducing propagates downstream in the direction of the cylinder wake. In the first papers on this topic authors suggested that the vortex wake flow formed by a streamlined body causes this effect. For flows with supersonic velocities adiabatic wall temperature decreasing was registered for flows around a cylinder behind circular ribs, on a plane surface behind obstacles in the form of a rib or a backward-facing step, on cones behind a sphere, cylinder, disk and cones of different sizes [9-11]. Cold regions in the wake flow behind the cut of turbine blade are also registered in the distribution of the stagnation temperature [13].

The research continues the experimental study of the previously recorded [14-18] effect of "aerodynamic cooling" of the wall (reduction of the temperature recovery factor) in the wake of a
streamlined body in a supersonic flow. The aim of this work is to study the heat transfer parameters in the supersonic wake flow of backward-facing step.

2. Experimental apparatus, instrumentation and technique
The studies were carried out at the AR-2 supersonic wind tunnel (Figure 2) with input flow Mach number 2.2 and a stagnation temperature of 294 K with a turbulent flow regime (Reynolds number over 20 million). The objective of the study was to determine the adiabatic wall temperature and heat transfer coefficient for supersonic flow around a smooth wall and in the wake behind the backward-facing step.

The supersonic wind tunnel working channel has a rectangular cross-section 70×98 mm (Figure 2). On the side walls of the working channel optical windows were mounted for visualization by an optical method using the shadow photographs (Figure 3). A flat model made of non-heat-conducting plexiglass (thermal conductivity coefficient was 0.19 W/(m·K)) to eliminate heat leakage in the longitudinal and transverse directions in order to increase the accuracy of measuring heat transfer parameters [19]. The model was installed on the lower wall parallel to the main flow. The heat transfer parameters were determined by varying the height of the step from 8 to 14 mm. The thickness of the unperturbed boundary layer during flow around a flat wall was about 6 mm.

The adiabatic wall temperature in the experiment is determined using the processing technique [20-22], which allows one to determine the heat flux into the wall already in the process of starting the wind tunnel and then extrapolate it to zero. The wall temperature in this case will be the adiabatic wall temperature. Information from all thermocouples and pressure meters of the experimental facility was collected in the temperature and pressure sensor blocks, then through amplifiers was directed toward the analog-digital converter. The automation program for experimental data obtaining and further processing was programmed in LabVIEW software and could be seen in the form of virtual instruments on the experimental monitor during each run of the wind tunnel.

The uncertainties of the main parameters were defined for 95% confidence interval [23]: ±0.5K for wall temperature, ±0.3K for flow stagnation temperature, ±6kPa for stagnation pressure, ±0.5kPa for
static pressure, ±1.2% for Mach number, ±2.7% for Reynolds number, ±1% for temperature recovery factor, ±9.5% for Stanton number.

3. Results and discussion
As a result of the experimental data processing, the Mach number in the flow, the adiabatic wall temperature, the heat flux, the temperature recovery factor and the Stanton number were calculated. Data in Figures 4 and 5 is presented for the case of continuous supersonic flow around plane model without the step and reflects the typical changing of the thermal gas dynamics parameters during the experiment.

Figure 4 shows a graph of change of total pressure in the pre-chamber of supersonic wind tunnel and static pressure on the model surface during the experiment. After opening the valve, launching the wind tunnel takes about 4 seconds, after which the pressure in the flow is set up and practically does not change during the experiment. The ratio of total and static pressure allows us to determine the Mach number of the input flow that is 2.2. All further experiments were carried out at the same input flow Mach number.

Figure 5 shows a graph of change of the total temperature, the model wall temperature and adiabatic wall temperature (obtained as a result of data processing) during the launching and operation of the wind tunnel. There was no possibility of heating the flow or the model during the experiment, so the initial model temperature was determined by the environmental conditions. The increase in the total temperature at the time of launching is due to the reaction of the thermocouple located in the pre-chamber to a sudden increase in pressure. As it can be seen, the input flow total temperature is getting set up more slowly than the pressure (Figure 4), but also remains almost constant in the course of the experiment. The model is cooled down by the flow and in the limit it can reach the adiabatic wall temperature, but in this experiment the state of thermal equilibrium was not achieved purposely during the study. Thus the heat transfer parameters were obtained by data processing technique [21, 22].
Figure 6 shows the temperature recovery factor calculations in the places of thermocouples mounting. The non-dimensional length of the model – the abscissa axis – was calculated as the ratio of the coordinate from the beginning of the model at the nozzle exit section to the corresponding height of the step (8-14 mm). An increase in the temperature recovery factor in comparison with the flow around the smooth model directly behind the step and a decrease in the wake flow were obtained. The maximum value of the temperature recovery factor reaches in the region of the boundary layer reattachment \( x/H = 2 \). This effect corresponds to the results of a previous research on the falling shock wave influence on the adiabatic wall temperature [14, 15]. At the same time, a decrease in the temperature recovery factor along the entire length of the model at a distance of up to 20 calibres downstream of the step is observed. As it can be seen the value of temperature recovery factor in the wake is the lower, the higher the height of the step. This effect correlates with the results of the research of the supersonic flow behind the rib [16-18], but the decrease in the temperature recovery factor is less pronounced.

![Figure 6](image)

**Figure 6.** Field distribution of temperature recovery factor along the dimensionless length of the plane model for supersonic wake flow behind a backward-facing step of varied height.

The heat transfer coefficient (Stanton number) behind the step, related to the heat transfer coefficient in the smooth model flow \( \text{St}/\text{St}_0 \), was less than 1 directly behind the step and increased as the distance from the step (Figure 7). Starting from the coordinate \( x/H = 3 \div 4 \), heat transfer enhancement is observed, remaining at the level of 20% over the entire measurement area along the length of the model – at a distance of up to 20 calibres downstream of the step.

![Figure 7](image)

**Figure 7.** Field distribution of Stanton number along the dimensionless length of the plane model for supersonic wake flow behind a backward-facing step of varied height.

Thus, in the area of the boundary layer reattachment behind the step, there is a maximum adiabatic wall temperature (temperature recovery factor) and a rather sharp increase in the heat transfer
coefficient. At the same time, at a considerable distance (up to 20 calibers) downstream, the cold wake flow region and the heat transfer enhancement are fixed. Perhaps this effect is associated with the entry into the boundary layer of high-speed low-temperature particles of the main flow, carried away by the recirculated flow behind the step. However, to confirm this hypothesis it is necessary to conduct additional research.

4. Conclusions
The results of an experimental study of heat transfer parameters for a supersonic flow in the wake of a backward-facing step are presented. The maximum temperature recovery coefficient and a sharp increase in the heat transfer coefficient in the region of the boundary layer reattachment at a distance of about 2 heights of the step were recorded. At a distance of up to 20 heights of the step downstream, there is a decrease in the temperature recovery coefficient down to 0.865 and the heat transfer enhancement at the level of 20% compared to the smooth model flow. The value of temperature recovery factor in the wake is the lower, the higher the height of the step.

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