Experimental study of the adiabatic wall temperature of a cylinder in a supersonic cross flow

S S Popovich, N A Kiselev, A G Zditovets and Y A Vinogradov

Institute of Mechanics, Lomonosov Moscow State University, Russia, 119192 Moscow, Michurinsky Prospect, 1

pss@imec.msu.ru

Abstract. The results of an experimental study of the adiabatic wall temperature for a supersonic air flow across the cylinder are presented. The temperature was measured contactlessly using an InfraTEC ImageIR 8855 thermal imager through a ZnSe infrared illuminator. The freestream Mach number was 3.0, input flow total temperature was 295 K, and the total pressure 615 kPa. The Reynolds number calculated from the cylinder diameter (30 mm) was about 10⁶. It is shown that it is possible in principle to determine the high-speed flow total temperature by defining the maximum temperature of a cylindrical probe at the front critical point. Thermograms of the wall temperature distribution along the profile of the cylinder were obtained. The research was performed at the experimental facilities of the Institute of Mechanics of Lomonosov Moscow State University.

1. Introduction

Determination of the adiabatic wall temperature - the temperature of the near-wall gas layers on a heat-insulated wall - is one of the main problems in the study of heat transfer in supersonic flows, since its direct measurement in the experiment is problematic [1, 2]. The value of the adiabatic wall temperature determines the magnitude and direction of the heat flux. In a dimensionless form, the adiabatic wall temperature is determined through the temperature recovery factor \( r \) (1), which shows the fraction of the dynamic temperature component \( \frac{u^2}{2C_p} \) recovered in the boundary layer [3].

\[
r = \frac{T_{aw}^* - T}{T_0 - T} = \frac{2C_p}{u^2}(T_{aw}^* - T). \tag{1}
\]

In the case of a flow around a plate, the difference between the adiabatic wall temperature and the flow total temperature is the greater, the greater the flow velocity and the more the Prandtl number differs from unity. For example, for an air flow (Pr=0.7) with a Mach number \( M=3 \), the adiabatic wall temperature is 0.93 of the undisturbed flow total temperature \( r=0.89 \). At the same time, when an incompressible (low-speed) gas flow is flowing around the plate, these temperatures are practically the same \( r=1 \). External influences (pressure gradient, wall permeability, surface shape and relief, shock waves, separated flows, condensation and evaporation of the working fluid) can lead to both an increase in aerodynamic heating in a localized area and a wall cooling [4-8].

An interesting effect of decreasing the temperature recovery factor was obtained in the work of Eckert and Weise, later described by Eckert in a review article on energy separation [9]. The authors experimentally investigated the transverse subsonic flow of a hollow cylinder with thermocouples...
pressed into its surface. At the front of the cylinder with a laminar boundary layer, the temperature recovery factor was as expected from theory. However, at a flow rotation angle of 180°, $r$ decreases to a value of -0.1, which means a decrease in the cylinder wall temperature below the thermodynamic temperature in the input flow. This phenomenon was called "aerodynamic cooling" by analogy with the effect of aerodynamic heating.

The results of the experiments of Eckert and Weise were at first questioned by L. Prandtl [9], but were soon confirmed by Ryan [10] and Thomann [11]. Ryan [10] also demonstrated that the effect of energy separation extends further on in the wake behind the cylinder. The problem of energy separation in a transverse flow across a cylinder was again investigated by Goldstein and He [12], Sanita and Goldstein [13]. The cylinder diameter was 28.55 mm, and the maximum flow velocity reached 100 m/s. The local wall temperature was measured with copper-constantan thermocouples along the circumference of the cylinder. The problem was also investigated by direct numerical simulation in the work of Aleksyuk and Osiptsov [14]. The range of the main considered parameters included: Reynolds number $Re<10^3$, Prandtl number $0.1<Pr<10$ and Mach number $M<0.6$, which corresponds to the periodic vortex shedding regime. In the region of supersonic velocities, Eber [15] investigated the flow around cones and cylinders in short-time tubes at Mach numbers 2.87 and 4.25. The paper [16] investigated the flow around a cylinder 1 inch (25.4 mm) in diameter with a fixed Mach number $M_0=3.9$ in the range of Reynolds numbers $Re_d=2.1\times10^4-6.7\times10^4$. Figure 1 shows a comparison of experimental results for subsonic and supersonic flow across a cylinder.

![Figure 1. Comparison of the results of measuring the temperature recovery factor of a cylinder in a subsonic (1-5) [9] or a supersonic cross flow (6-9) [15, 16].](image)

As seen from figure 1, the adiabatic wall temperature is equal to the flow total temperature at the front critical point ($\phi=1$) for both subsonic flow velocities and supersonic ones. According to the works of Eber [15], Walter and Lange [17], the temperature recovery factor does not decrease so much around the cylinder profile at supersonic velocity, in contrast to subsonic one. In this case, the value at the rear critical point increases from 0.1 to 0.87 when the Mach number changes from 0.5 to 2.5. In [16], on the contrary, the recovery factor varied from 1 at the front critical point on the cylinder to 0.67 at a bypass angle of 120° and then again tends to 1 at the rear critical point.
This work is aimed at investigating the potential for reducing the temperature recovery factor in a supersonic transverse flow across a cylinder. The data of previous studies are contradictory, while the potential for temperature reduction in a supersonic flow is much greater than in a subsonic one, since the dynamic temperature component is much larger. Flow effect resulting in low values of temperature recovery factor can make it possible to propose new ways of energy separation [18-21] and reduction of aerodynamic heating in compressible gas flows.

2. Methodology
The experimental study is carried out on the basis of the AR-2 supersonic wind tunnel [22, 23]. The working part of the installation has a rectangular cross-section with dimensions of 70 × 98 mm (Fig. 2). The freestream Mach number is \( M_0 = 3.0 \). Total flow temperature was 295 K, total pressure – 615 kPa. The Reynolds number, calculated from the cylinder diameter, was about \( 10^6 \).

![Figure 2](image)

Figure 2. a) Scheme of the experimental facility: 1 – prechamber; 2 – assembly of cones; 3 – honeycomb; 4 – sensor for measuring total pressure; 5 – thermocouple for measuring total temperature; 6 – working channel; 7 – flat adjustable supersonic nozzle; 8 – static pressure and temperature sensors; 9 – infrared thermal imager; 10 – ZnSe illuminator; 11 – optical glass illuminator, 12 – model cylinder, 13 – plexiglass bottom wall; 14 – diffuser; b) 3D-design of the model cylinder.

The capacity of the compressor feeding the installation (up to 10 kg/s) makes it possible to maintain constant parameters of the main flow in the working section for about an hour or more and to carry out experiments practically in steady-state regime. The side walls of the channel are formed by a set of flat plates, among which there are plates with round windows with optical protective glasses. Rearrangement of the plates makes it possible to position the plates with illuminators in the required places of the working section and to visualize and photograph the flow pattern. Also, instead of the side wall of the test section of the wind tunnel, an infrared illuminator was installed, made of a ZnSe polycrystal, a material transparent to the infrared region of the spectrum. Thus, it was possible to carry out a contactless survey with the InfraTEC ImageIR 8855 thermal imager of the model cylinder.

The investigated cylinder was made of photopolymer resin on a UNIZ 3D printer, which made it possible at the stage of 3D solid modeling to provide channels for sampling static pressure and supplying thermocouples to the investigated bypass of the cylinder profile. The cylinder diameter is 30 mm. To exclude the influence of the growing boundary layer on the bottom wall, the cylinder was removed on a narrow foot from the flow to a height of 30 mm.

3. Results and discussion
As a result of the investigations carried out, a number of thermograms of the temperature distribution along the profile of the cylinder were obtained (Fig. 3). In this case, the study was carried out in a steady-state regime, i.e. readings were taken after thermal equilibrium was established. The supersonic
Flow was directed from left to right. The contour of the profile in the middle of the cylinder height was considered in order to exclude the influence of the upper and lower edges. The cold spot in the upper part of the thermogram is a reflection of the thermal imager matrix.

**Figure 3.** Thermogram of a supersonic flow around a cylinder.

**Figure 4.** Distribution of the ratio of the adiabatic wall temperature to the input supersonic flow total temperature along the profile of the cylinder.

Fig. 4 shows the distribution of the temperature recovery factor calculated from the measured local wall temperature and the parameters of the input flow. As in the previously mentioned works [15-17], it can be seen that the temperature value at the front critical point of the cylinder is practically equal to the flow total temperature measured in the prechamber of a supersonic wind tunnel (as is known, the flow total temperature does not change during expansion in the Laval nozzle). Based on this result, it is possible to propose a method for measuring the temperature of a high-speed flow by measuring the maximum temperature (at the front critical point) of cylindrical probes. Such measurements can be carried out both by pressing a thermocouple in the front of the cylinder and non-contacting using a thermal imager through an illuminator. However, this method of measuring the total temperature in a
supersonic flow does not allow measuring the total temperature profile in the boundary layer, since the cylinder in this case becomes a source of disturbances in the near-wall region.

In figure 1, Graph 10 shows the distribution of the temperature recovery factor obtained in the experiment according to the data in figure 4. The wall temperature along the cylinder profile decreases from the total temperature (r=1) - at the front critical point of the cylinder to the level of the adiabatic wall temperature specific for a turbulent flow around a smooth wall (r=0.89) - in the preseparation region. In the boundary layer separation region, a local maximum temperature is observed and a further decrease to a level slightly lower (r=0.87) - at the rear critical point of the cylinder. Thus, a significant effect of a wall cooling, by analogy with subsonic flow velocities, has not been revealed at the moment for a supersonic flow velocity.

Acknowledgements
This work is supported by the Russian Science Foundation (Grant 19-79-10213).

References
[1] Hayes J R and Neumann R D 1992 AIAA PrAA 142
[2] Kutateladze S S and Leontiev A I 1990 Heat Transfer, Mass Transfer, and Friction in Turbulent Boundary Layers (Taylor and Francis)
[3] Shapiro Ascher H 1953 The Dynamics and Thermodynamics of Compressible Fluid Flow, Ronald Press. Vol. 2. New York, 553 p.
[4] Leontiev A I, Popovich S S, Vinogradov U A and Strongin M M 2018 JPCS 1129
[5] Leontiev A, Popovich S, Strongin M and Vinogradov Y 2017 EPJ Web Conf 159
[6] Leontiev A I, Popovich S S, Vinogradov U A and Strongin M M 2019 JPCS 1369 012040
[7] Vinogradov Y A, Zditovets A G, Kiselev N A, Medvetskaya N V and Popovich S S 2020 Fluid Dynamics 55 5
[8] Popovich S S, Zditovets A G, Kiselev N A and Vinogradov Y A 2020 JPCS 1683 022064
[9] Eckert E R G 1986 Int Commun Heat Mass Transf 13
[10] Ryan L F 1951 Experiments on aerodynamic cooling (Ph. D. thesis, Eidgen. Tech. Hockschule, Zurich)
[11] Thomann H 1959 The Aeronautical Research Institute of Sweden FFA Report 84
[12] Goldstein R J and Boyong He 2001 Transactions of the ASME 123
[13] Sanitjia S and Goldstein R J 2004 Int J Heat Mass Transf 47
[14] Aleksyuk A I and Osiptsov A N 2018 Int J Heat Mass Transf 119
[15] Eber G 1941 German Archive Report 66/57
[16] Goodwin G, Creager M O and Winkler E L 1956 NACA RM A55H31
[17] Walter L W and Lange A H 1953 NAVORD Rep. 2854 (U.S. Naval Ordnance Lab)
[18] Burtsnev S A and Leontiev A I 2014 High Temp 52 pp 297–307
[19] Leontiev A I, Zditovets A G, Kiselev N A, Vinogradov Y A and Strongin M M 2019 Exp Therm Fluid Sci 105
[20] Makarov M and Makarova S 2017 MATEC Web of Conferences 33rd Siberian Thermophysical Seminar 09001
[21] Aleksyuk A I 2021 J Fluid Mech 915
[22] Vinogradov Y A, Zditovets A G, Leontiev A I, Popovich S S and Strongin M M 2017 JPCS 891
[23] Leontiev A I, Popovich S S, Vinogradov U A and Strongin M M 2018 Proc 16th Int Heat Transf Conf 212244 (Beijing)