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Influence of Free Stream Inhomogeneity on Heat Flux and Temperature on a Plate in a Supersonic Flow

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Abstract

Influence of density inhomogeneity of supersonic flow on heat flux and temperature on a plate has been studied experimentally. The inhomogeneity of the supersonic free stream was obtained by injection of a thin helium jet into the main air stream. Such approach allows to model impact of an infinitely long heated stream of gas, with lower density than gas of the main flow, on body aerodynamics. Reorganization of the gas flow around the body leads to the considerable change of power loading and a heat flux. Results of a research of a heat transfer coefficient are discussed.

Keywords: *gas dynamic, density inhomogeneity, heat flux.*

Nomenclature

Latin
M – Mach number
Nu – Nusselt number
Pr – Prandtl number
P – Pressure
Re – Reynolds number
T_0 – Stagnation temperature
T_r – Recovery temperature
T – Temperature
h – Heat transfer coefficient
r – Temperature recovery coefficient
v – Flow velocity
Greek
α – Angle between the shock wave and the axis of the flow

1. Introduction

Searching for techniques to reduce power and thermal loads on the body becomes more and more relevant with increasing an aircraft flight speed. There are gas-dynamics methods to control flow around a body at a supersonic speed with separated flows and returned flows significantly reducing drag of blunt bodies, for instance, with a mechanical needle or an air jet flowing from the top of the blunt body towards to a main supersonic flow. Since the mid-40s of the last century some researches and studies of an impact of long thin channels with low-density, located in front of the bow shock wave, on restructuring of gas-dynamic flow around the body were carried out [1]. Lately, the use of a variety of discharges (laser, microwave, glow) to manage the supersonic flow were of a significant

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interest [2]. An application of discharges is considered to be promising in many aerospace technologies: control of the aerodynamic characteristics of an aircraft, obtaining an effective method for reducing drag, mixing and ignition of gases in the propulsion system and many others. A review of research in these areas may be found, for instance, in [3, 4].

It was theoretically [5] and experimentally [6] found that the main factor leading to restructuring of flow around a body is heating the gas after being discharged. Thus, the system of Euler's equations and the perfect gas model usually used in a computer simulation of the discharge interaction with the bow shock [4], and gas heating in the discharge region is determined by the ratio of the gas densities in the discharge area and free stream. At the same time, if in a numerical simulation there are no obstacles in studying the heated gas region of any length, then in experimental research creation of the heated region of the quasi-infinite length is of some difficulty.

There was an investigation which showed that injection of thin jet of gas with lower density in the main stream leads to the same results as in the experiments with discharges but with longer duration [7]. In that research helium was used as low density gas.

This paper is aimed at studying of influence of free stream density inhomogeneity on heat flux and temperature on a plate in a supersonic flow.

2. Equipment

2.1. Experimental setup

The experimental research was conducted on a setup described in [6]. The scheme of setup is presented in Fig. 1. To solve the problem there was mounted an additional section 3 between prechamber 1 and nozzle 2. The prechamber of helium 4 was placed in this additional section and was connected to a vacuum gauge 7 by tube 6 and to a helium tank 10 through reducer 8 and valve 8 by tube 5. The helium tank could be disconnected to supply air from atmosphere by the tube. Besides that, there were made two different tips for the helium prechamber. Both of the tips could be placed at the front of the helium prechamber and had tubes to supply gases to the edge of the nozzle. One of them had tube with conical expanding portion at the end to form a supersonic expiry of air with Mach number approximately 2.3. Another tip had normal tube to supply helium. All tubes had internal and external diameter of 2 mm and 3 mm respectively.

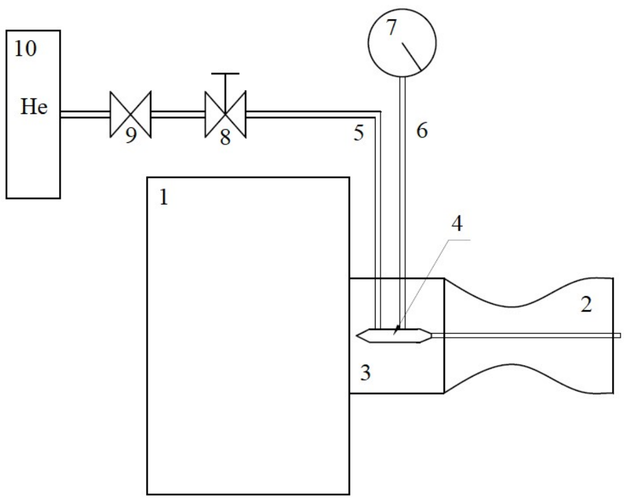

Fig. 1 Experimental setup scheme

The profiled nozzle with Mach number 2.1 was used to form the main stream. The pressure in the main stream was measured with a vacuum gauge and equaled to about P=40 Torr. The stagnation temperature of both air and helium was T_0=290 K.

Fig. 2 Experimental setup (without nozzle)

2.2. Diagnostic equipment

The investigation of shock wave interaction with density inhomogeneity before the model was carried out using the Schlieren method. Images of the flow were recorded by a PCO Dicam Pro digital video camera with a resolution of 1024x1024 pixels. System of synchronization and control was built on the universal data acquisition board of NI USB 6343.

Gradient heat flux sensor, which was used in the experiments, was made of monocrystalline bismuth in the St. Petersburg Polytechnic University named after Peter the Great. The work of the sensor is based on the transverse Seebeck effect. Size of the sensor is 2,3x2,3 mm, thickness is 0.4 mm. A plastic washer with the diameter of 6 mm and thickness of 1 mm was placed between the sensor and the rod.

Chromel-copelic thermocouple was used to measure temperature of the model surface.

A plate made of ABS plastic on a 3D printer Picaso in the resource centre of applied aerodynamics of St. Petersburg state University was used as a model. Surface of the plate (30x45mm pulled along the stream) was placed at an angle of 15 degrees to the flow direction. Heat flux sensor was located on the model axis at the distance of 25mm from the edge of the plate. Thermocouple was set up at the distance of 32mm from the edge of the plate behind the heat flux sensor.

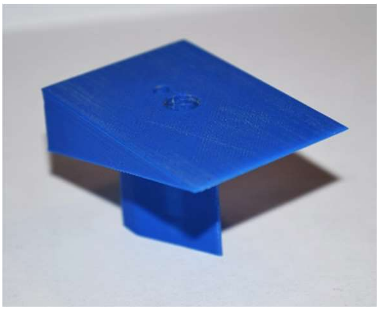

Fig. 3 Experimental model

3. Experimental research

3.1. Preparations for the Experiment with Helium

It was necessary to create working flow with a thin helium jet on the axis for conducting the experiments. Velocity of the helium jet at the edge of the tube was ought to be equal with free stream velocity to guaranty modelling thermal inhomogeneity without additional disturbances. The geometric and gas-dynamic parameters, which were essential for obtaining required expiration mode, were calculated. Calculations showed that density of helium at the outlet of the tube was equal to 0.01 kg/m^3, which was 0.08 of the air density in the main stream. Additionally, calculations demonstrated that helium expiration was supposed to be subsonic. Developed technique was tested on supplying of thin air jet in the working flow. Flow parameters were measured with optic and pneumometric ways.

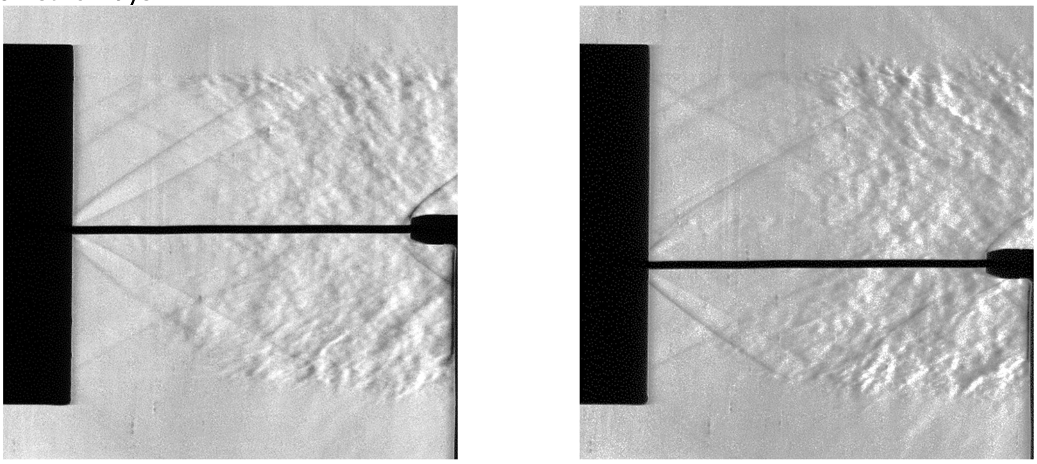

Fig. 4 Measuring of parameters of the flow with the air jet

Left picture: the Pitot probe was positioned immediately behind the air supply tube into the working flow. Right picture: the Pitot probe was offset below the flow axis. One could see on the axis of the working flow slight disturbances produced by boundary layer on the tube. Experiments showed that injection of the air jet to the free stream is able to be done without significant disturbance of working flow. The same technique was used in experiments with helium and allowed to reach working flow with density inhomogeneity on its axis.

3.2. Experimental results

There were conducted experiments in which impulse mode of helium supply was implemented. Helium expired to the edge of the model. Calculated parameters of the flow on the model surface are listed below: Mach number along the surface is M=1.54, velocity of the flow is v=433 m/s, temperature is T=196 K, pressure is P=1215 Pa, local Reynolds number (x=25 mm) is $Re=1.8 \cdot 10^5$ what corresponds to laminar flow in the boundary layer. Prandtl number on the plate (for air) is Pr=0.7. That corresponds to temperature recovery coefficient r=0.84 and recovery temperature T_r=275 K.

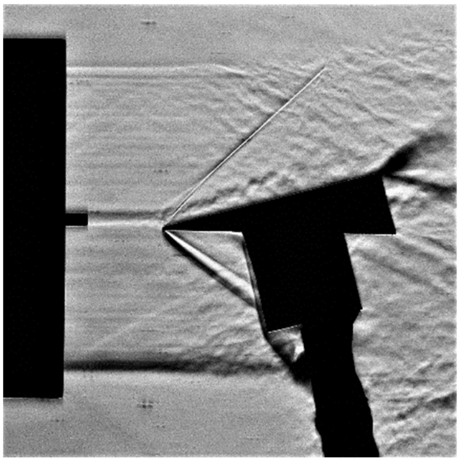

Fig. 5 Flow around the model

Distortion of the shock wave could be observed as a result of interaction with density inhomogeneity. Shock wave is curved with upstream bulge. Additionally, it could be seen that there was turbulent flow in the boundary layer instead of laminar. Obviously, the appearance of vortices was a consequence of Richtmeyer-Meshkov instability in the interaction of the density inhomogeneity of the incoming flow with the shock wave on the body [4].

Dependence of heat flux and temperature on time is shown on the graph below where heat flux is in W/mm^2 and multiplied by 3000, temperature is in degrees of Celsius, and time is in seconds.

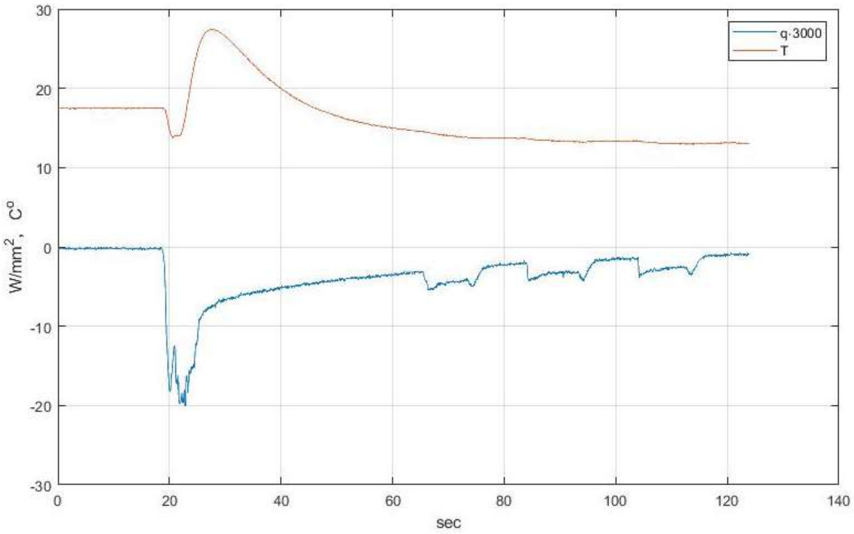

Fig. 6 Dependence of heat flux and temperature on time

Could be seen that after the setup is in working mode there is approach of heat flux to zero and approach of temperature to constant. In addition, there are three helium supplying pulses which lead to decrease of the heat flux in 1.5 times for the first pulse and in 2.5 times for the third pulse. Calculations showed that from 70th to 120th seconds heat transfer coefficient h varied from 30 to 140 W/(m^2·K) and Nusselt number varied from 50 to 210. Also could be noticed that these changes in the heat flux were not enough to make visible changes in temperature.

Additionally, there were conducted the experiments in which the plate was set up along with the flow axis. And as in the previous experiments there was the impulse mode of helium supplying.

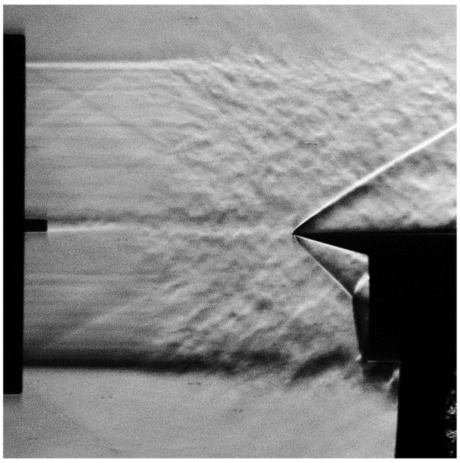

Fig. 6 Flow around the model along the flow axis

In this case angle between shock wave and flow direction is α=30°, that is in a good agreement with the angle determined by the ratio

$$\sin\alpha = \frac{1}{M}$$

It means that shock wave turned into an infinitely weak wave. In this case helium supplying did not lead to significant disturbances around the model. Dependence of heat flux and temperature on time is shown on the graph below.

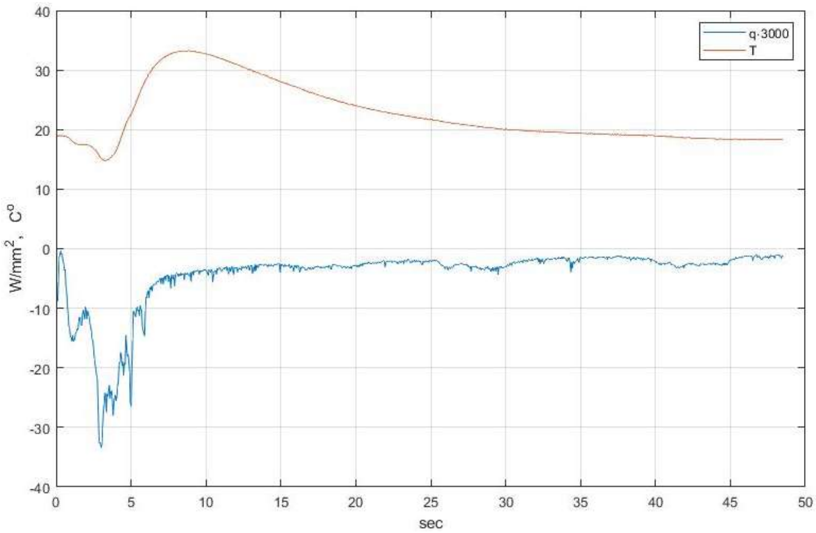

Fig. 7 Dependence of heat flux and temperature of the model along the stream on time

On this graph could be seen that injection of helium had almost no influence on the heat flux and the temperature. From 15th to 45th seconds three periods of slight decrease in heat flux could be observed. Calculations showed that in this period heat transfer coefficient varied from 20 to 50 W/(m^2·K) and Nusselt number varied from 30 to 70.

4. Conclusion

This technique (the introduction of a thin stream of light gas into the wind tunnel working flow) may be useful in studying the influence of heated gas region, which has an infinite length, on the aerodynamic characteristics of the body. Experiments have shown that changes in the gas-dynamic structure of the gas near the supersonic body, due to the appearance of Richtmayer-Meshkov instability, lead to a significant change in heat fluxes on the surface.

Acknowledgments

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