Heat flux on streamlined body surface after local energy input

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Abstract. An experimental and numerical study of interaction between an oblique shock wave and density inhomogeneity is done. The inhomogeneity is created by interelectrode spark discharge in the oncoming flow with a Mach number of 2. As a result of the experiment, we obtained gradient heat flux sensor data and took shadow photography of the process.

1. Introduction

Local energy input into a supersonic gas flow has been considered for a long time as a promising method for controlling the flow around various bodies and creating control torques. Early studies of this method began in the middle of the last century. Since then, a large number of works have been carried out to study the effect of local energy deposition on various bodies aerodynamics [1,2].

Commonly the main subjects of the analysis are the consequences of interaction between a heated gas region with a shockwave on the body, such as, for example, a drop in stagnation pressure and vorticity formation. The intensity of the vortex is determined by the ratio of densities of the heated gas and gas of oncoming flow [3]. In work [4] a numerical simulation of the interaction between the gas domain heated by microwave and laser discharges, and blunt cylinder was carried out. It is shown that when the heated gas region begins to touch the shock wave, then on a boundary of the heated region density and pressure gradient vectors cease to be collinear and formation of a vortex begins. At the same time, the shock wave begins to move along the hot tunnel towards an oncoming stream. Since vortex formation takes place at the interface between two media with different densities during the passage of the shock wave, this vortex structure can be attributed to Richtmyer-Meshkov instability. As a result of the further passage of the hot track upstream, a pressure drop occurs at the critical point of the cylinder and the surface pressure distribution as a whole changes. In experimental studies [5,6] it was shown that using an optical discharge of a femtosecond laser, it is possible to reduce drag of a blunted cone by 50%. In various works, the possibility of creating control moments was considered, for example, in [7], the influence of the location of an optical discharge on the aerodynamics of a cone-shaped body with a half-opening angle of 15 degrees was investigated using numerical simulation.

In this experimental study, we use an electric interelectrode discharge to create a local heating area in supersonic oncoming flow. We took shadow photographs of the interaction between oncoming flow inhomogeneity with an oblique shock wave. We measured local heat flux on the plate surface with use of a bismuth-based gradient sensor. Also, a numerical simulation of the process was carried out and we made a comparison of the calculated pressure contours with shadow photographs of the process.
2. Experimental investigation
The experimental study was carried out on a supersonic wind tunnel with an Eiffel working chamber. The working flow was formed by a profiled nozzle with a Mach number of 2.1. Flow diameter 60 mm, static pressure 40 Torr. The experimental model surface is at an angle of 22 degrees to the oncoming flow velocity vector.

To implement the energy input into the flow, we used an interelectrode spark discharge, the discharge voltage is 20 kV and the current is 25 A. One of the electrodes was brought to the nose of the experimental model, the other was in front of it upstream. The distance between the electrodes was 8 mm.

We used a gradient heat flux sensor based on a bismuth single crystal, manufactured at the Peter the Great St. Petersburg Polytechnic University to measure the heat flux. The sensor is based on the Seebeck effect [8]. The area of the sensor working surface is 4 mm$^2$, the thickness is 0.2 mm. It was installed on the symmetry axis of the experimental model at a distance of 5 mm from the nose (Figure 1).

![Figure 1](image)

Figure 1. Elements location on the experimental model: 1 – electrode, 2 – heat flow sensor, 3 – thermocouple.

2.1. Experimental results
As a result of the experiment, we obtained shadow photographs of the process. In Figure 2 we can observe formation and movement of the discharge trace. When density inhomogeneity interacts with the shock wave, you can see how the shock wave bends as it moves. After this, the inhomogeneity runs along the body surface. We can observe that flow is rearranged near the body surface after the interaction of the inhomogeneity with the shock wave.

During the experiment, we received data from a gradient heat flow sensor. Knowing the voltage generated in the sensor, we found the temperature difference on the sensor surfaces. To process the experimental data, we solved the non-stationary heat transfer equation for an infinite plate, knowing the temperature difference on the sensor surfaces [9]. In Figure 3 shows the experimental data and the heat flux density change. On the graphs, we see electrical noise after 10 microseconds. After about 50 microseconds, the heated gas reaches the sensor surface and we see an increase in heat flux. Depending on the angle of inclination of the discharge, it is possible to obtain not only an increase but also a decrease in the heat flux.
3. Numerical simulation

3.1. Problem formulation

We perform numerical simulation of the interaction of a shock wave with a heated gas within the model of a perfect viscous gas. The system of three-dimensional Navier-Stokes equations was solved using the k-ω SST turbulence model. We used the Sutherland equation to take into account the change in gas viscosity with temperature. The computational domain consists of 1.92 million cells (Figure 4), the data on the undisturbed flow are taken from the experiment. To speed up the calculation, the problem was solved relative to the symmetry plane. We make the calculation, assuming that the discharge energy used to increase the internal gas energy is 0.157 mJ.

Figure 2. Shadow photographs at the moment of discharge and 25/45/70 μs after.

Figure 3. Experimental (left) and processed (right) data from the heat flux sensor after the discharge at an angle of 0 (red line), 10 (green line), 20 (blue line) degrees to the oncoming flow velocity vector.
3.2. Comparison of calculation results with experimental data

Figure 5 shows a comparison of the calculated pressure contours and shadow photographs. We see that shock waves are diverging from the discharge region. They are less intense than the shock wave on the body, so they pass over it.

![Figure 5](image)

**Figure 5.** Comparison of calculated pressure contours and shadow photos at the moment of discharge and after 5/10 μs.

In Figure 6, we can see a comparison of the normalized heat flux density data and the average integral temperature at the sensor area from the calculation. Data normalization is presented in (1), where $T(t)$ is the calculated temperature and $T_{\text{norm}}(t)$ is the normalized values.

$$T_{\text{norm}}(t) = \frac{T(t) - T(0)}{\max(T(t) - T(0))}$$  \hspace{1cm} (1)

The discharge is located collinear to the oncoming flow velocity vector. Calculated temperature peak corresponds to the time at which the discharge trace passes over the sensor surface. At the same time, due to convective heat transfer, the heat flux density begins to increase, then decreasing to the stationary flow level.
Figure 6. Normalized calculated average temperature on the sensor surface (blue line) and the experimental heat flux (red line) when the discharge is collinear to the oncoming flow velocity vector.

4. Conclusions
We carried out the experimental study of the heat flux with the help of a gradient sensor. Obtained data indicate the possibility of changing the heat flux density on the body surface using a pulsed electric discharge. With a relatively short discharge duration of 2.5 μs, we obtain a significant disturbance of the flow near the surface of the streamlined body. Numerical simulation of the process was also carried out; comparison with experimental data showed a good agreement between the calculated pressure contours and shadow photographs.

Acknowledgments
This work was supported by the Russian Foundation for Basic Research (grant No. 19-31-90071). Research was carried out using computational resources provided by the Resource Center “Computer Center of SPbU”.

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