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Study of effects from local energy deposition in supersonic gas flow on well-streamlined body

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Abstract

This work devoted to the investigation of effects that occur after local energy deposition in supersonic gas flow in front of a streamlined body. The energy deposition was produced by using electrical discharges. We carried out a numerical simulation and experimental work of the interaction between heated gas volume and shockwave on the body. As a result of this, one was observed significant flow changes near the body.

Keywords: *energy deposition, supersonic, well-streamlined body*

Nomenclature

t – flow time

T_f – integral of temperature over the wedge front side

T_i – integral of T_f over time

V – flow velocity vector

β – angle between heated area and V

1. Introduction

Aerodynamic quality of a flying vehicle decreases with increase in the Mach number because of mechanical energy loss to overcome wave resistance [1]. Experimental investigations showed that the lift-to-drag ratio value, which can be achieved by changing shape of an aerodynamic profile, is approximately equal to 4 at hypersonic speeds [2]. Therefore, the other methods of flow controlling were investigated to improve the aerodynamic characteristics of a flying vehicle. One of the methods is to make an energy deposition in supersonic flow. Depending on the task specifics it can be carried out in the various ways, for example, by using a laser-induced optical breakdown or an electrical discharge. After the energy input, heated rarefied gas region is formed. As a result of the interaction between heated gas and shockwave on the body, a flow pattern significantly changes. This method of flow control has potential to solve problems of super- and hypersonic flight, since it has a high speed reaction and the possibility of a targeted influence, which allows getting predictable changes in the required flow parameters.

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 works [4, 5], a numerical simulation of the interaction between gas

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region, which 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. These effects are confirmed by experimental investigations [6, 7], in which change of flow nature and pressure at the critical point of cylinder after the microwave discharge is studied. A study was also carried out on the change in heat flux at a stagnation point of a cylinder after microwave discharge, as a result of which the drop in heat flux after energy input into the flow was shown [8].

2. Experiment

The experiment was carried out in a supersonic wind tunnel. Mach number is 2.1, static pressure of oncoming flow is 40 Torr, static temperature is 162 K. The line passing through the ends of the two electrodes (Fig. 1) makes an angle of 46 degrees with the flow velocity vector V. Apex angle of the wedge is 14 degrees. The voltage applied to the electrode is 20 kV, resistance is 800 Ω and pulse duration is 2.5 μs.

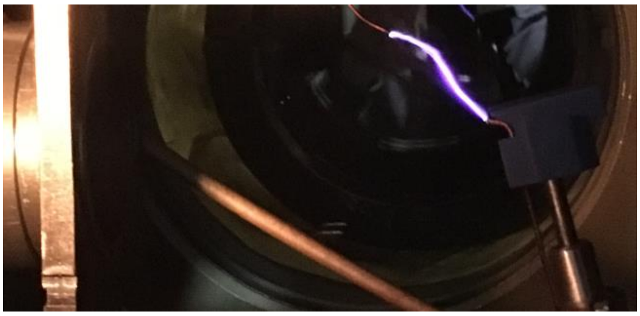

Fig 1. Electrical discharge in supersonic flow

In Fig. 2 shows formation and movement of the discharge trace. You can observe how the shockwave bends as it moves.

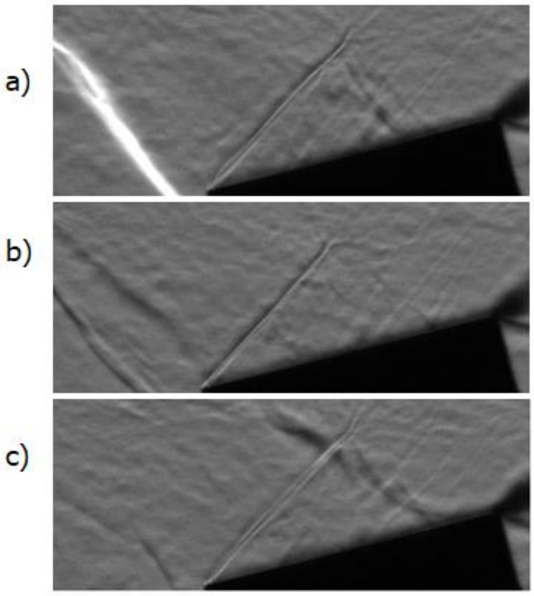

Fig 2. Flow images near the wedge at a) 0 μs; b) 5 μs; c) 50 μs after discharge

3. Numerical simulation

Numerical calculations were carried out in Ansys Fluent. 3-D simulation showed that changes in gas-dynamic parameters are most pronounced in a symmetry plane of the wedge, therefore, planar problems with different configurations of the heated region were considered. The equation of ideal gas state, k-ω SST turbulence model and Sutherland equation are used for solving. Roe-FDS scheme was used for flux calculating. Flow parameters are the same as in the experiment. Temperature of the heated area is 500 K, length is 10 mm and diameter is 1 mm. In Fig. 3 shows the diagram of the computational domain. Calculation series was carried out, during which the angle β was changing in the interval [0, 60] with 15-degrees step.

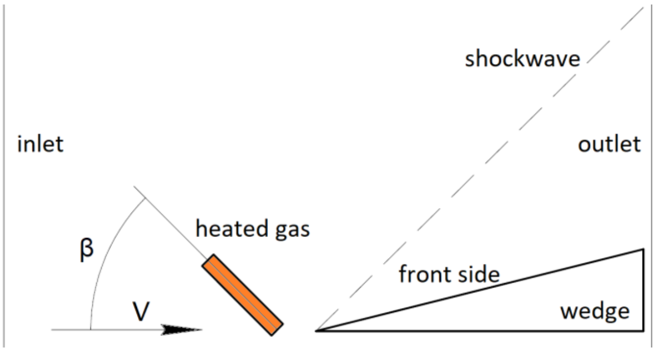

Fig 3. Diagram of the computational domain

Let denote integral of temperature over the wedge front side as T_f (Eq. 1). And relative percent change of T_f is equal to Eq. 2.

$$T_f(t) = \int_{frontside} T(x,t)dx \tag{1}$$

$$\left(\frac{T_f(t)}{T_f(0)} - 1\right) * 100 \tag{2}$$

Integral of T_f over time is denoted as T_i (Eq. 3).

$$T_i(t) = \int_0^{tend} T_f(t)\, dt \tag{3}$$

In Fig. 4 shows a relative change of the T_f. As you can see, when β is 0 the temperature increases significantly more than in the other cases.

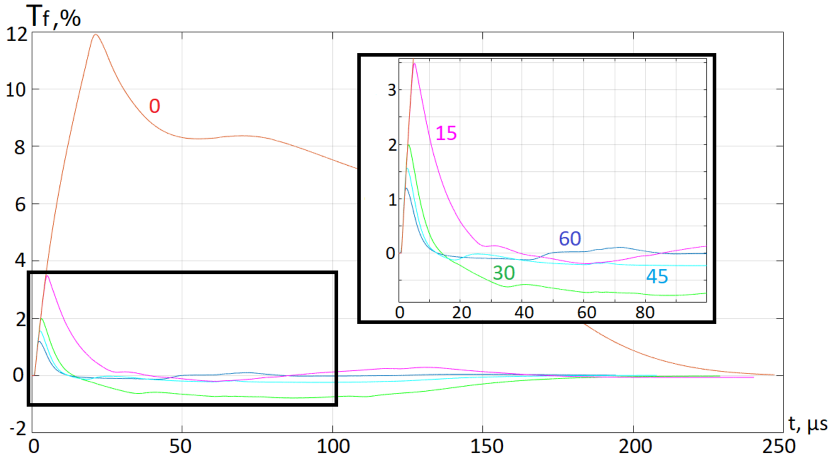

Fig 4. Relative change of T_f for different angles β

If we integrate T_f over time for every angle in relation to the initial temperature distribution, we can see (Fig. 5) that the most effective angle β for reduce temperature near the wedge front side is 30 degrees.

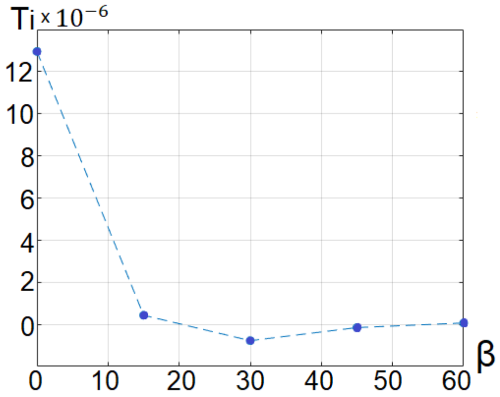

Fig 5. Change of T_i depending on the angle β

Now let us consider relative motion behind the shock wave. For doing that, we subtract the velocity vector behind the shock wave from a velocity field. As a result, we can see the vortex structure, which was formed after the contact of the hot gas with the shock wave (Fig. 6). Maximum speed in the vortex is 169 m/s. As the vortex moves, pressure and temperature fields near front side of the wedge will change, and an intensity of the vortex will decrease.

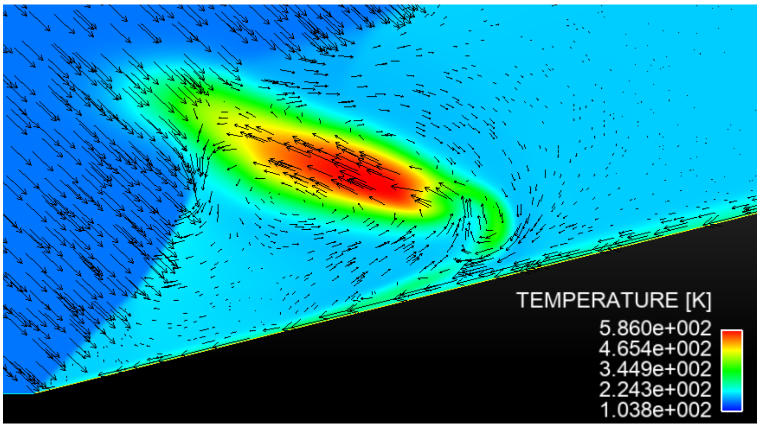

Fig 6. Temperature and velocity fields at t = 21 μs, β = 30 degrees

4. Conclusions

Numerical simulations had shown that it is better to place the discharge area at an angle to the flow in case of the wedge. Optimal value of the discharge inclination angle to reduce the gas temperature near the wedge surface was found.

The experimental stand was prepared, so we could create a discharge in the desired geometric configuration. The experimental work was performed with a discharge with inclination angle of 45°. Flow images after the discharge showed the inhomogeneity that moving along the oblique shockwave. Numerical simulation showed similar flow pattern after the energy deposition to the flow.

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