Front separation regions for blunt and streamlined bodies initiated by temperature wake – bow shock wave interaction

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Summary. Front separation flows supported by an upstream energy deposition are examined. It is shown that a reason for separation region formation is an interaction of a thin high temperature wake ("thermal spike") which is formed downstream a localized energy deposition region with a shock layer upstream of a body. Some simplified analytical models are applied to describe a front separation phenomenon. To realize steady flows with isobaric front separation regions in numerical experiments the "method of transformation of energy deposition" is proposed. The method is applied for both blunt as well as streamlined "thermal spiked" bodies to realize conical front separation regions. "Shock-free" separation flows initiated by subsonic "thermal spikes" are particularly examined.

Introduction

Historically an idea of improvement of aerodynamic characteristics of bodies by a localized energy deposition in an upstream supersonic flow was proposed in Russia in the meddle 80-ies. From the very beginning a local energy deposition was considered as an instrument for control of a supersonic flow over large bodies. In this case the mechanism of a wave drag reduction was a formation of front separation regions ahead of a fore surface of bodies.

Georgievsky, Levin [1] and Yuriev et al. [2] have shown the possibility of wave drag reduction for blunt bodies. Stabilization of an optical discharge in a supersonic flow of argon that was obtained by Tretiyakov et al. [3] was the first experimental confirmation for the possibility of the controlled electrodeless energy deposition in a high speed flow. Nemchinov et al. [4] has found a "forerunner" effect for a shock wave – a rarefied channel interaction, and has formulated the "thermal spike" conception for wave drag reduction of blunt bodies. The model of "steady isobaric front separation region" was introduced by Guvernjuk, Savinov [5]. The possibility of an effective control of flows over blunt and streamlined bodies by a localized energy deposition in an upstream flow in a steady and a pulse-periodic modes was shown by Georgievsky, Levin [6, 7]. Term "effective" means, that a small energy deposition into a small region upstream of a large body produces a wave drag reduction, when the saved power is much higher than a consumed one. The recent surveys for application of an upstream energy deposition for supersonic aerodynamics problems were performed by Zheltovodov [8] and Knight et al. [9].

1 Formulation of the problem

To describe supersonic flows with an energy deposition the mathematical model of the "energy source" was applied. Euler equations for an unsteady motion of an inviscid perfect gas presented in a vector form are:

$$\frac{\partial\rho}{\partial t}+\operatorname{div}\rho\mathbf{V}=0,\ \frac{d\mathbf{V}}{dt}+\frac{1}{\rho}\operatorname{grad}p=0,\ \frac{\partial e}{\partial t}+\operatorname{div}(e+p)\mathbf{V}=\rho Q,\ e=\frac{p}{\gamma-1}+\frac{\rho\mathbf{V}^2}{2} \quad (1)$$

where p is the static pressure, ρ is the density, $\mathbf{V}$ is the velocity vector, e is the total energy per volume unit and Q is the energy input per mass unit per time.

Only axially symmetrical flows were examined. Depending on a problem specific cylindrical r, z or spherical R, θ coordinates were applied. The energy input Q in cylindrical coordinates is defined by:

$$Q(r,z,t)=Q_0 f(t)\exp\left(-\left(\frac{r}{\Delta r}\right)^2-\left(\frac{z-z_0}{\Delta z}\right)^2\right) \quad (2)$$

where Q_0 is the magnitude, $\Delta r, \Delta z$ are "effective radii" and z_0 is the location of the energy source center on the symmetry axes. It must be noticed, that a space distribution (2) is of "Gaussian type", so that $\dot{Q} > 0$ for each point in a calculation region. But it is not a problem for numerical simulation because of exponential decreasing of the energy input with a distance from the energy source center.

For a flow over the energy source without a downstream body the similarity criteria can be formulated:

$$\gamma=\text{const},\ M_\infty=\text{const},\ Q_0\Delta z=\text{const},\ \frac{\Delta r}{\Delta z}=\text{const} \quad (3)$$

The explicit MacCormack scheme [10] of a second order accuracy with coordinates and time (for interior points on smooth solutions) was used for a numerical simulation. Discontinuities (shock waves and tangential surfaces) were not specially allocated and were calculated using regular algorithm. Typical parameters for an upstream flow were $\gamma = 1.4, M_\infty = 2$. The time marching procedure was used to establish steady solutions or to examine unsteady processes. Courant-Friedrichs-Lewy stability condition was used to determine the time step. Spherical coordinates were used for blunt bodies and cylindrical coordinates – for streamlined bodies. Mesh resolution was depended on the situation and typically was 400×360 points for spherical coordinates R, θ and 400×800 for cylindrical coordinates r, z.

2 Simplified schemes for front separation regions formation

In the present paper the Guvernjuk, Savinov [5] model of the "isobaric front separation region" was be applied to found separation region geometry in the presence of the high temperature wake. If the energy source cross size approaches to zero, whereas the similarity conditions (3) are held, then the temperature and other gasdynamics parameters on the symmetry axes are constant (cross direction distributions are self-similar). At the limit the separation region becomes conical (Fig.1, left). According with [5] it was assumed that the static pressure inside conical separation region was equal to a total pressure in the wake behind the locally normal shock (or simply the total pressure for subsonic wake). Depending on the "thermal spike" heating parameter ω the front separation region angle α, the oblique shock angle β and conical flow in the shock layer were determined.

Nemchinov et al. [4] "forerunner" scheme for a normal shock – a high temperature wake interaction is presented on Fig.1 (right). For the initial moment of the contact of

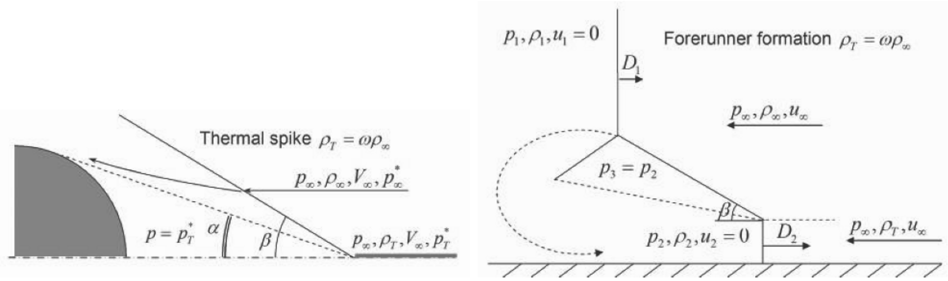

Fig. 1. Simplified schemes for front separation regions formation: left – the "thermal spike" scheme for the conical front separation region; right – the "forerunner" scheme for the normal shock – the high temperature wake interaction.

the primary normal shock with a high temperature cloud the situation of the "random discontinuity decomposition" is taking place. So the secondary normal shock moves upstream the temperature wake with the velocity D_2, that is higher than the primary shock velocity D_1 . So the two-dimensional unsteady structure with oblique shock and triple point configuration appears. Nemchinov et al. [4] have found wonderful in its simplicity formula for the oblique shock angle β:

$$\sin\beta = \sqrt{\omega} \tag{4}$$

The flow scheme, presented on Fig.1 (right), shows the turn-inside effect for the stream formed by the gas particles passed through the oblique shock (the "forerunner stream").

3 Front separation regions formation for blunt bodies

If the energy source is "powered on" in the uniform upstream flow, then the high temperature cloud appears. The elongation of the cloud is provided by the drifting effect of the upstream flow and by the acceleration of hot particles by the pressure gradient behind the bow shock (if the "flow choking effect" is observed [6]). In any case when the cloud contacts the shock layer the process of the high temperature wake – the shock layer interaction starts. The initial stage of this process can be described by the Nemchinov "forerunner" model, so the "forerunner stream" appears (the blunt body can be considered as a reason for a normal shock existence). If similarity criteria (3) are satisfied for different size energy sources, then on this stage flowfields looks very similar. If the temperature wake is enough thick, then the stream spreads over the lateral surface of the body and the steady isobaric front separation region forms. But for thin temperature wakes the "forerunner stream" turns inside the front separation region – this way the circulating flow arises (Fig.2, left). The constant inflow of additional gas into the separation region results in its enlargement in a cross direction with the next periodical blowout of an extra gas – the pulsations of front separation region appears (Fig.2, right). That's why Nemchinov et al. [4] have made a conclusion, that only pulsing regimes are realizable for front separation regions initiated by the "thermal spike".

To realize steady flows with isobaric front separation regions in numerical experiments the "method of transformation of energy deposition" is proposed. Initially, the steady solution with the isobaric front separation region was found for the enough large energy

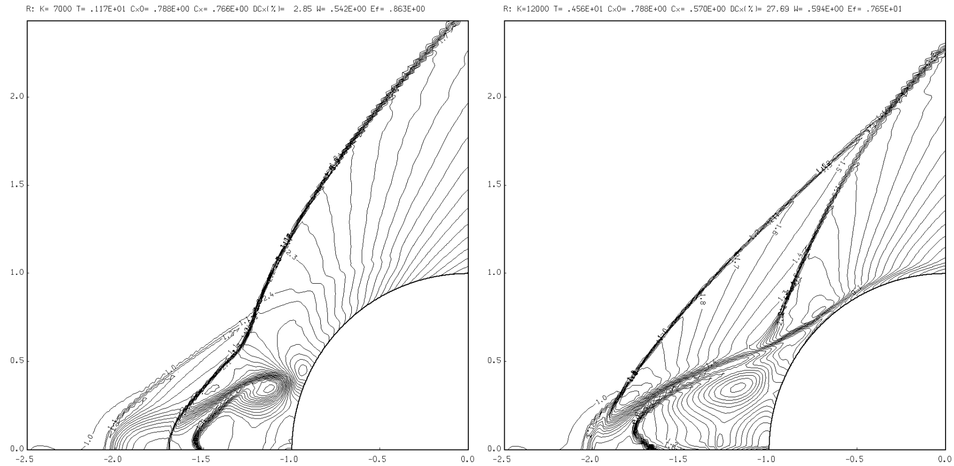

Fig. 2. Formation of pulsing separation regions for blunt bodies: left – the "forerunner stream" turns inside the front separation region; right – the enlargement of front separation region in cross direction (density isolines).

source. Then the energy source radius was decreased from the large value down to the small one (similarity criteria (3) were held). Finally the flow with the accurate isobaric front separation region for the small energy source (Fig.3, left) was found instead of the pulsing flow, that was observed when the same energy source was "powered on" in the uniform upstream flow (Fig.2, right).

Similar idea was applied to find "shock-free" regimes for the flow over the sphere. "Shock-free" deceleration regimes are characterized by a continuous deceleration of a

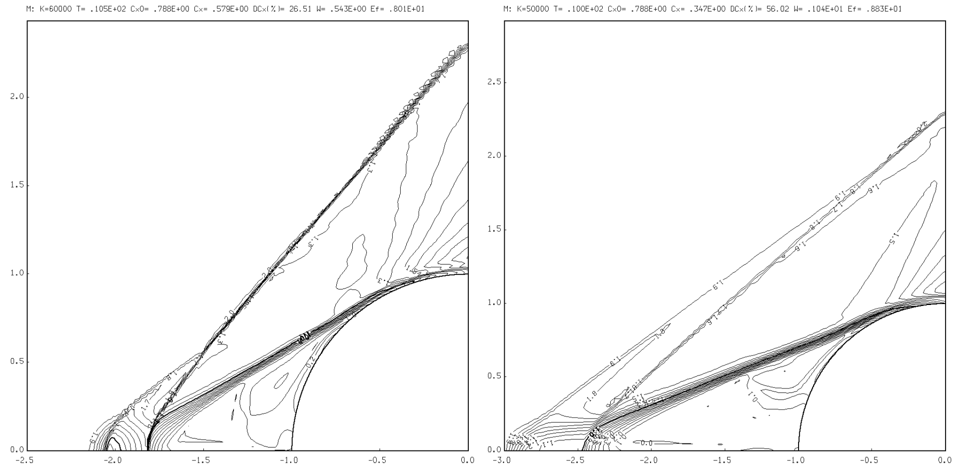

Fig. 3. Flows with steady isobaric front separation regions initiated by thin temperature wakes, that were calculated by the "method of transformation of energy deposition": left – spherical energy source; right – elongated energy source, "shock-free" regime (Mach numbers isolines).

flow inside a temperature wake from a supersonic speed down to a subsonic one so that only weak hanging shock appears on the periphery of a flow. Such regimes were observed in [6] for a supersonic flow over elongated energy sources. But if the elongated energy source is powered on in the uniform upstream flow, then because of the “forerunner stream” capturing effect a very unstable pulsing flow was observed. On Fig.3 (right) the same energy source was compressed from a large spherical source during the numerical procedure. This way the accurate steady flow with the isobaric conical front separation region was found.

4 Front separation regions formation for streamlined bodies

The supersonic flows over streamlined bodies of the unit midsection where examined. Class of ogival-type bodies was constructed by the rotation of the circle arc around the arc chord.

For energy sources of a small elongation (for spherical energy sources for example) the “flow choking” effect is taking place [6], supersonic temperature wakes arise and regular flow regimes are observed. No separation regions appear and hot particles are spread around the lateral surface of the body. In the temperature wake region the obliquity of the apex shock changes or, if the ogival body apex angle is larger than the critical for the local Mach number in the temperature wake, the bow shock appears (Fig.4, left).

For elongated energy sources the “shock-free” deceleration effect is taking place, subsonic temperature wakes arise [6] and the situation radically changes. The irregular regimes are observed for the flows over ogival bodies (Fig.4, right). The stable composite-type conical front separation regions appear – partially the regions are filled by the high temperature slow moving gas and partially by the slow vortex flow. The “shock-free” regime is realized – only hanging shocks appears on the periphery of the flow (according to the new “effective” body shape). It must be mentioned that the effect of “forerunner stream” capturing was observed for very thin temperature wakes only. The flow for $\Delta r = 0.1$ was calculated by the “direct” powering on the energy source in the uniform flow and the “transformation” method was applied for Fig.4, (right) $\Delta r = 0.1 \rightarrow \Delta r = 0.05$. Thus the energy deposition into an elongated region can be used for initiation of front separation regions for streamlined bodies.

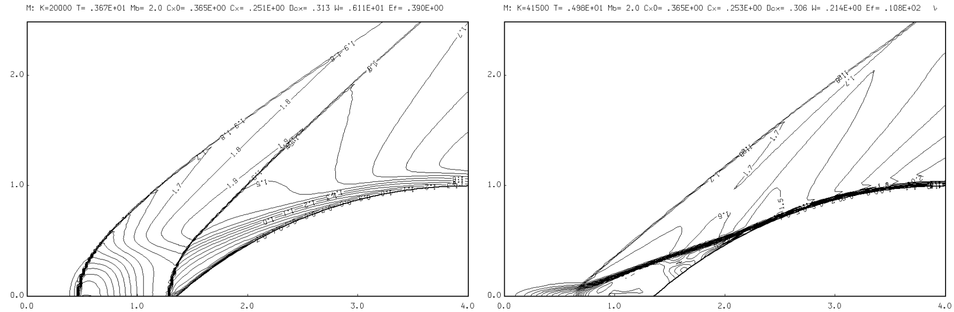

Fig. 4. Regular and irregular flows over the ogival-type body: left – spherical energy source, thick temperature wake; right – elongated energy source, thin temperature wake (Mach numbers isolines).

Conclusions

Front separation flows supported by an upstream energy deposition are examined. It is shown that a reason for separation region formation is an interaction of a thin high temperature wake which is formed downstream a localized energy deposition region (or the "thermal spike") with a shock layer upstream of a body. The Guvernjuk-Savinov model of isobaric front separation region was applied for the analytical describing of the conical flow over "thermal spiked" bodies. The Nemchinov "forerunner" model was used for explanation of the effect of "forerunner stream" formation during the temperature wake – the shock layer interaction. It was shown that the "forerunner stream" formation is a reason for pulsations of front separation regions. To realize steady flows with isobaric front separation regions in numerical experiments the "method of transformation of energy deposition" is proposed. The method is applied for both blunt as well as streamlined "thermal spiked" bodies to realize conical front separation regions. "Shock-free" separation flows initiated by subsonic "thermal spikes" are particularly examined.

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