Impact of a thermally stratified energy source on the bow shock wave and aerodynamic characteristics of a body

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Abstract. This paper presents numerical modelling of a thermally stratified energy source’s effect on the supersonic flow past a body “double-wedge - plate”. A multiple generation of the Richtmyer-Meshkov instabilities was obtained. These instabilities cause almost complete destruction of the bow shock front inside the source area and form a new multi-vortex mechanism of affecting the streamlined body. The defining parameters of the effect of stratified and homogeneous energy sources with equal values of total energy are analysed. The possibility of a significant decrease in the temperature at the vertex of the double-wedge and in the average front surface temperature due to the redistribution of source energy between layers has been established.

1. Introduction

The area of supersonic/hypersonic flow control due to energy deposition into different regions of a flow currently occupies one of the leading positions in the field of aerospace engineering [1-3]. A problem of flow control for the unsteady flow past a sphere was proposed and studied in [4]. The concept of a heat spike was introduced as the most effective form of energy release in the external flow to influence the aerodynamic characteristics of a body. The effect of a longitudinal heated channel on the supersonic flow past a blunted body was studied in [5] and the change in its wave drag was examined. The influence of a focused energy deposition in the external flow which changed the upstream shock structure was researched in [6]. The effects of essential wave drag reduction and of a very high power effectiveness were established for hypersonic flows. The mechanism of decreasing the drag force of a blunted body under the action of a vortex caused by an external longitudinal energy source was established in [7] when simulating experiments on microwave effects on the flow. The laser pulse as an instrument of flow control was proposed in [8]. The study of the effect of thermal regions initiated by laser and microwave heating in supersonic flow past a blunted body was carried out in [9]. Recent investigations in this area focus on the effects of combined energy sources. A double-vortex mechanism under the influence of a double longitudinal thermal pulse was obtained in [10]. The effect of a double laser pulse on the drag forces given that the next pulse moves through the plasma created by the previous one was studied in [11]. The blurring of the front of a reflected shock wave in a boundary layer exposed to a structure of extended plasma formations induced by an electric discharge (Q-DC discharge) was experimentally registered in [12].

The effect of a thermally stratified region initiated by an ionization unstable glow discharge on an initially flat shock wave in a shock tube was experimentally and numerically investigated in [13]. Under the influence of the regions initiated by large-scale ionization strata, the curvature of the shock wave...
front was established. Small-scale temperature regions caused the complete disappearance of the shock wave front in the schlieren pictures in the interaction zone. In the numerical simulation of the experiment, the multiple generation of the Richtmyer-Meshkov [14, 15] instabilities was shown. Under the influence of said instabilities the shock wave front (in the density field) practically ceased to exist, which explained the results of the experiment.

In this paper, the effects accompanying the impact of a thermally stratified energy source on the bow shock wave and the characteristics of a streamlined body in a supersonic flow are obtained and studied.

2. Methodology

A numerical simulation of the effect of a thermally stratified energy source on the supersonic flow past a pointed plate is performed. The full system of Navier-Stokes equations for a viscous heat-conducting perfect gas is solved numerically (air, γ=1.4) [16]

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} = 0$$

$$\mathbf{U} = \left( \begin{array}{c} \rho \\ \rho u \\ \rho v \\ \rho E \end{array} \right), \quad \mathbf{F} = \left( \begin{array}{c} \rho u \\ p + \rho u^2 \\ \rho uv \\ \rho u(E + p) \end{array} \right), \quad \mathbf{G} = \left( \begin{array}{c} \rho v \\ 
\mu v \\ p + \rho v^2 \\ v(E + p) \end{array} \right)$$

$$\mathbf{F}_v = -\left( \begin{array}{c} 0 \\ \mu / \text{Re}(4/3u_x - 2/3v_y) \\ \mu / \text{Re}(v_x + u_y) \\ \mu \pi_1 / \text{Re} + (1/N)kT_x \end{array} \right), \quad \mathbf{G}_v = -\left( \begin{array}{c} 0 \\ \mu / \text{Re}(v_x + u_y) \\ \mu / \text{Re}(4/3v_y - 2/3u_x) \\ \mu \pi_2 / \text{Re} + (1/N)kT_y \end{array} \right)$$

$$\pi_1 = u(4/3u_x - 2/3v_y) + v(v_x + u_y), \quad \pi_2 = v(4/3v_y - 2/3u_x) + u(v_x + u_y)$$

$$E = \rho(\varepsilon + 0.5(u^2 + v^2)), \quad N = \text{RePr}((\gamma - 1)/\gamma),$$

where Re is the Reynolds number and Pr is the Prandtl number (Pr=0.703). Here ρ, p, u, v are the gas density, pressure, x- and y- velocity components; ε is the specific internal energy,

$$\varepsilon = p/(\rho(\gamma - 1)).$$

The dependence of the dynamic viscosity μ on temperature T is approximated by the Sutherland's law,

$$\mu = T^{1.5}(1 + s_1)/(T + s_1),$$

with the constant $s_1=0.41$ (120K). It is assumed that the coefficient of thermal conductivity k depends on temperature as

$$k = T^{0.5}.$$
\[ \rho_i = \alpha_i \rho_\infty, \quad \alpha_i < 1. \]

The pressure and velocity components were set equal to their values in the oncoming flow (indicated by the index \( \infty \)),

\[ p_i = p_\infty, \quad u_i = u_\infty, \quad v_i = 0. \]

The temperature inside the layers was elevated compared to its value in the oncoming flow,

\[ T_i = \alpha_i^{-1} T_\infty. \]

At the boundaries of the body, the adhesion conditions, \( u=0, v=0 \), and the conditions for the absence of flows normal to the boundaries were used. At the entrance boundary, the conditions of the oncoming flow were set, and at the exit boundaries, the absence of flows of corresponding parameters in the directions normal to the boundaries was assumed.

![Figure 1](image)

**Figure 1.** Dynamics of the density field during the interaction of a stratified energy source with a shock layer produced by a pointed body, \( t=0.601 \): a) \( t=0.65 \); b) \( t=0.75 \); c) \( t=0.85 \); d) \( t=1.05 \)

The calculations were performed using the program code based on the complex conservative difference schemes of the second-order approximation [17], which are constructed using systems of differential consequences on \( x \) and \( y \) of the basic system of equations. The schemes are different at the boundaries of the body and in the flow while the conservative properties are preserved throughout the
calculation area. The Cartesian staggered grids with equal space steps were utilized; the transverse body size accounted for 480 nodes ($9.5 \times 10^6$ nodes in the calculated area counting the central node of the stencil). Examples of the scheme verification and grid convergence for similar problems and the same set of grids are presented in [17].

3. Results

Figure 1 shows the dynamics of interaction of a stratified energy source with a shock layer formed by a double-wedge-pointed plate in a supersonic flow with Mach number $M_\infty = 2$. Here $\alpha = 0.3$ in all layers. The formation of the curved precursor front [5] inside the area of the energy source can be observed (Figs. 1a-1c, time instants are indicated in the images). Note that at the initial stage of the interaction, the Richtmyer-Meshkov instability appears in gas density fields (Figs. 1a, 1b). The origin of the Richtmyer-Meshkov instability in problems with an external longitudinal energy source was discovered and studied in [18]. Then there is the development of vortex (mushroom-like) structures which interact with the frontal surface of the body (Fig. 1c). A vortex structure consisting of many vortices interacts with the frontal surface of the body causing drops in drag force and in stagnation pressure (at the vertex of the double wedge). Thus, the mechanism of a stratified energy source’s influence on the surface of a streamlined body is multi-vortex. Later the vortex structure is completely absorbed by the shock layer (Fig. 1d). Then it is removed from the calculated area and the flow returns to an undisturbed state.

The surface views of the density field (at $t = 0.75$ and $t = 0.85$) are shown in Figs. 2a, 2b where the peaks corresponding to the development of the Richtmyer-Meshkov instability are discovered. The precursor front is curved and wavy in the source zone and almost completely destroyed due to generation of the instability.

![Figure 2. Density fields (surface view), a) – $t = 0.75$; b) – $t = 0.85$](image)

A homogeneous energy source that coincides in size and value of total energy with the stratified source was considered, as well. In this case, the mechanism of action of the homogeneous source was associated with the vortex-free interaction of the shock layer with the thermal region (Fig. 3). Here, the precursor front exists, it is not destroyed in the source zone and the instability doesn’t arise. Figure 4 demonstrates the flow images for stratified (red) and homogeneous (blue) energy sources in isochores superimposed on each other. It can be seen that vortex structures in the flow, produced by the stratified energy source, are forming in the area of presence of a contact discontinuity in the flow for a homogeneous source performing a new (multi-vortex) type of influence on the body surface. It should be noted that the amount of the instability peaks increases in time with the growth of the precursor inside the source zone. At the same time their amplitudes decrease.
Figure 3. Dynamics of the density field during the interaction of a homogeneous energy source with a shock layer produced by a pointed body, $t=0.601$: a) $-t=0.75$; b) $-t=0.85$; c) $-t=0.95$; d) $-t=1.05$

Figure 4. Fields of density for stratified (red) and homogeneous (blue) energy sources, isochores: a) $-t=0.75$ b) $-t=0.85$
Figure 5 presents the differences at the points \((x_i, y_j)\) between the fields of temperature for homogeneous and stratified energy sources, \(\Delta T(i, j) = T_h(i, j) - T_s(i, j)\). The calculations show that, as the source formed heated region moves forward in the shock layer, the temperature on the front body surface becomes less for a stratified source compared to a homogeneous one. Indeed, when \(t=1.0\) \(T_s\) is less than \(T_h\) only in the area of the vertex of the double wedge (violet) (Fig. 5a). Then the area of reduced values of temperature on the front surface increases (Figs. 5b - 5c) and by the time \(t=1.2\) \(T_s\) becomes less than \(T_h\) on the entire front surface of the body (violet) (Fig. 5d).

![Figure 5](image)

**Figure 5.** Dynamics of difference between the temperature fields for homogeneous and stratified energy sources during the interaction with a shock layer: a) \(-t=1.0\); b) \(-t=1.1\); c) \(-t=1.15\); d) \(-t=1.2\)

Figure 6 shows a comparison of the dynamics of stagnation pressure and density at the vertex of the double wedge (indicated by an index \(st\)) (Fig. 6a), drag force of the front surface \(F\) (Fig. 6b), stagnation temperature (Fig. 6c) and average temperature on the surface of the double wedge \(T_a\) (Fig. 6d) for stratified and homogeneous energy sources. Here

\[
T_a = \frac{1}{N} \sum^{N} T_k,
\]

where \(T_k\) is the temperature value at the \(k\)-point on the front wedge surface and \(N\) is a number of grid points on the front surface.

The analysis of the calculation results is summarized in Table 1. This analysis reveals that given a slight difference in pressure and density behavior at the vertex of the double wedge in the range of the source action (Fig. 6a) the difference in the drag force of the wedge-shaped surface is also insignificant, 6.5% relative to the frontal drag force in the absence of a source or 1.1 times in time-averaged values.
(see the dashed lines) (Fig. 6b). At the same time, the difference in temperature at the vertex of the wedge is significant and the temperature in the case of the stratified energy source is 78% less than that in the case of the homogeneous one (relative to the stagnation temperature in the absence of a source) or 1.6 times less (in time-averaged values) (Fig. 6c). Dynamics of the average temperature on the front surface $T_a$ is shown in Fig. 6d. It can be seen that $T_a$ for the stratified energy source is 32% less than that

![Figure 6](image_url)

**Figure 6.** Dynamics of pressure $p_{st}$, density $\rho_{st}$ (a) at the vertex of the double wedge; front drag force $F$ (b); temperature $T_{st}$ (c) and averaged temperature of the front surface $T_a$ (d); red curve - stratified source, blue curve - homogeneous source; dashed lines – time-averaged values at the intervals of changing

**Table 1.** Time-averaged values for decreased drag force $F$ and increased temperature $T$

| Value     | Stratified source, $f_s$ | Homogeneous source, $f_h$ | Without a source, $f_0$ | Relative difference, $\frac{\text{abs}(f_s - f_h)f_0}{100}$%
|-----------|--------------------------|---------------------------|-------------------------|---------------------------------|
| $F$       | 0.7335                   | 0.6577                    | 1.1622                  | 6.52%                           |
| $T_{st}$  | 2.5394                   | 3.9949                    | 1.8652                  | 78.03%                          |
| $T_a$     | 4.5671                   | 5.6928                    | 3.5048                  | 32.11%                          |
for the homogeneous one (relative to the value of $T_o$ in the absence of an energy source) or 1.25 times less (in time-averaged values). In addition, the maximum $T_o$ at the whole-time interval is less than this value for the homogeneous one by 1.5 times (Fig. 6d).

Therefore, the conducted calculations showed that using a stratified energy source, despite a small loss in reduction of drag force, gives an undoubted benefit in reducing the temperature of gas near the frontal surface of a body.

Conclusions

The effect of a thermally stratified energy source on the supersonic flow past a double-wedge pointed plate was numerically studied at $M=2$. Comparison analysis with the effect of the homogeneous energy source with the same total energy has been conducted. The obtained new results are as follows:
- A multiple generation of the Richtmyer-Meshkov instability is obtained, which distinguishes a stratified energy source effect on aerodynamic parameters of a body from the influence of a homogeneous source with the same spatial characteristics.
- Almost complete destruction of the bow shock wave in density field via the multiple generation of the Richtmyer-Meshkov instabilities in the region of a stratified energy source has been achieved.
- A new multi-vortex mechanism of a stratified energy source impact on aerodynamic characteristics of a body has been established.
- It was found that in comparison to a homogeneous source the effect of a stratified one (having the same total energy and spatial characteristics), in spite of a slight loss in the drop of the frontal surface drag (1.1 times), is a significant decrease in stagnation temperature at the vertex of the double wedge (1.6 times) as well as a decrease in the average front surface temperature (up to 1.5 times).

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