FLOW INVESTIGATION IN COMBUSTOR CHAMBER WITH BACKWARD - FACING STEP
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Introduction

Supersonic scramjet is the basic component of the future high-speed transport systems. The process of fuel ignition in the combustor chamber is very important since it influences essentially on aircraft efficiency.

A hypersonic flow is braking when passing through an inlet and an isolator, and at the entrance of the combustor chamber has moderately supersonic speeds (M=2÷3). At such a speed, the characteristic times of mixture residence in combustor chamber are small. The oxidant temperature in the area of fuel supply has to be high enough to provide mixture ignition and burning.

A channel with expansion (backward facing step or cavity) is a traditional geometrical configuration to organize subsonic recirculation zones used for combustion stabilization in a supersonic flow [1]. It is supposed, that the needed static flow temperature in the ignition area can be provided by high total temperature T0>1500K. Nevertheless, as investigations show, temperature fields of high-enthalpy flows in the vicinity of channel expansion are rather non-uniform. Expansion fans, cold channel walls, an injection of cold fuel or a wall heat-protection by means of cold jets can result in a formation of local relatively cold and hot zones.

During last decades, numerous analytical, numerical and experimental investigations of supersonic flows over cavity and backward-facing steps have been performed [2-4]. In [5] the detailed investigation of influence of wall temperature on the separation flows over as sphere and cylinder was carried out. At the same time, the data concerning the temperature factor influences on flow parameters over backward-facing step are limited. These results would have special importance for high-enthalpy flows in short duration facilities for which a relative wall temperature is changing significantly during the experimental run.

The main goal of the paper is to study the temperature fields and the temperature factor (K_T=T_w/T0) effects on properties of supersonic flows in vicinity of BFS. Several series of computations have been performed under the conditions of hot-shot wind tunnel at incoming Mach numbers M∞=2, 2.5 and 3.5. Skin friction and static pressure distributions along the surface have been obtained for several values of a temperature factor. The flows are numerically simulated on the basis of the unsteady Favre-averaged Navier-Stokes equations complemented with Wilcox k-ω [6] model. The original numerical algorithm [7] was used with the temporal approximation based on four-step finite-difference scheme of fractional steps. The TVD Flux Vector Splitting scheme by van Leer [8] of the third order of accuracy has been used. To ensure the numerical simulations give reliable results, the verification have been carried out for various configurations with Shock Wave /Boundary Layer Interaction such as forward - facing steps [9], impinging shock wave [10], cylinder–flare configuration [11], inlets [12] etc.

The numerical investigations are carried out under the conditions of hot-shot wind tunnel IT-302M ITAM SB RAS. The parameters of flows are presented in Table 1. Here M∞ is a free stream Mach number before step, P0 and T0 are total pressure and temperature, h stands for a step height, Re is a Reynolds number, P∞, U∞, T∞ are freestream static pressure, velocity and static temperature, T_{wad} is a wall adiabatic temperature for present conditions.

Table 1. Flow parameters.

<table>
<thead>
<tr>
<th>№</th>
<th>M∞</th>
<th>h, mm</th>
<th>P0, MPa</th>
<th>T0, K</th>
<th>Re×10^5</th>
<th>P∞</th>
<th>U∞, m/c</th>
<th>T∞, K</th>
<th>T_{wad}</th>
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<td>1</td>
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<td>1.5</td>
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<td>1035</td>
<td>667</td>
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<tr>
<td>2</td>
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<td>2</td>
<td>1600</td>
<td>5.6</td>
<td>0.114</td>
<td>1336</td>
<td>711</td>
<td>1502</td>
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<tr>
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<td>25</td>
<td>13.0</td>
<td>3000</td>
<td>9.4</td>
<td>0.172</td>
<td>2069</td>
<td>869</td>
<td>2766</td>
</tr>
</tbody>
</table>

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The computation domain (Fig. 1) was restricted by inlet (1) and outlet (2) sections, rigid wall (3) and free artificial boundary (4) on the top. The inlet section (1) was chosen downstream from the transition region and upstream from the interaction zone to provide there undisturbed turbulent boundary layer which integral parameters were close to those in the experiments. At the outlet section so called “soft” conditions were used. At the top boundary, the non-reflecting “simple-wave” conditions for all the gasdynamic parameters were used. At rigid surface (3), the no-slip velocity and temperature conditions of two types were specified. The first type was the adiabatic temperature condition $\partial T / \partial n = 0$, and the second type was constant temperature $T_{wall}^V = T_w$. A rectangular grid was used in calculations, condensed to the rigid walls and consisted of 200÷300 nodes in y-direction and 300÷500 nodes in x-direction. The minimal x and y grid steps near the surface were about $10^{-4}$ that provides a proper resolution of the laminar sub-layer of turbulent boundary layer near the rigid walls.

**Simulation Results**

At Mach number $M_\infty = 2$ the adiabatic and cold wall conditions with $T_w = 300$, 500 и 700 K were used. Static pressure and skin friction distributions along model are presented in Fig. 2. Pressure and skin friction were normalized by their values before the step. Points $x/h = 0$ and $x/h = 1$ correspond to the external and internal corners of the configuration. Figure shows, that for a cold wall $T_w = 300 K$ (Fig. 2a, line 1), the base pressure is higher by a factor 1.5 comparing to that under the adiabatic conditions. When $T_w$ is increasing from 300K to 700K, the base pressure level is reduced and pressure recovers to the theoretical level faster, which testifies on the reduction of the separation zone size (Fig. 2a). The skin friction distribution (Fig. 2b) also confirms the separation zone shortening. The further growth of wall temperature $700K < T_w < 1200K$ leads to some increase of the separation zone sizes and the base pressure level. Non-uniform skin friction behavior inside of separation zone at $1 < x/h < 3$ indicates on the secondary separation in the vicinity of vertical wall.

In order to estimate an influence of wall temperature in the recirculation zone, the temperature fields were analyzed for different temperature factor $K_T$ (Fig.3). For all considered temperature factors the highest temperature values were observed in the reattachment point. From the reattachment zone, hot gas is carried inside the separation zone by recirculation vortex. At the same
time, the temperature of mixing layer for all $K_T$ was closed to freestream static temperature. For adiabatic wall conditions (Fig.3.a), a three-vortex configuration is formed in the separation zone with the small clockwise vortex in the inner corner, rather big counter clockwise middle vortex with temperature of about 1000K and the clockwise vortex adjusted to the external flow. At $T_w=900K$ (Fig. 3 b), the first vortex disappears, the second vortex reduces in sizes and the third external vortex grows. For the cold wall conditions $T_w=300K$, the three-vortex structure appears again. The temperature level in the separation zone is essentially lower than that under the adiabatic conditions (Fig. 3d).

Figure 3. Temperature fields and streamlines in the recirculation zone at $M_\infty=2$

Figure 4 shows the results obtained at $M_\infty=2.5$ under cold wall conditions $T_w=300K$. The computed static pressure and skin friction distributions (lines) are presented together with experimental results (markers). The comparison of calculated results and experimental data has shown that the computations correctly predict the length of separation. Disagreement in the base pressure levels may stem from high measurement errors in the experiments under low static pressure conditions. The analysis of streamline behavior gives that at this Mach number the flow patterns are similar to those described above at $M_\infty=2$. 
The computed density field and experimental shadowgraph for this case (Fig. 5, a, b) permit one to juxtapose flowstructures in the computations and experiments. All the typical flow features like expansion fan (EF), mixing layer (ML), recirculation zone (RZ) and tail shock wave (TSW) can easily be seen in the figures. The computation truly reproduces the main flow features like size of recirculation zone, the slope of the shock etc. But in the experiment, the mixing layer and the reattached boundary layer are thicker that those in the computations. The recirculation zone consists of two vortexes that can be seen both in the computations and the experiments.

Next series of calculations were performed at $M_\infty=3.5$ and total temperature $T_0=3000K$. All the patterns of the base pressure and separation zone size behavior described above are kept. It is necessary to note a substantial growth of separation zone size for $T_w=300K$ (Fig.4, a, line 1) that is connected with a significantly low $K_\Gamma$ and a large difference between external flow static and wall temperatures.
For adiabatic and moderately cold temperature conditions, a pressure recovery after the reattachment point is non-uniform. The reason of this phenomenon is the secondary compression waves arising in the region of tail shock and shear layer interaction [14]. As it was shown in [14], in the vicinity of external expansion corner the flow splits into two layers. The inner low-speed low-density near-wall layer forms the rare base region. The second external layer with higher density forms the jet-like mixing layer. When the tail shock passes through the jet-like mixing layer, secondary compression waves originate that further come to the wall and lead to a non-monotone pressure recovery.

In Figure 5, the static pressure contours is presented for $M_\infty=3.5$, $T_w=700K$. Fifty pressure contours are shown in the range of $2\cdot10^4-2\cdot10^5$. The secondary compression waves (SW) described above could be seen together with EF, RZ and TSW.

The positions of three cross-sections are also shown in Fig.5 with arrows, where the profiles of gas-dynamics and turbulent parameters were analyzed. The profiles of temperature, density, velocity and turbulent kinetic energy in the section S1 located before the interaction are presented in Fig. 6. The change of temperature factor $K_T$ affects all the parameters. Under adiabatic conditions, the large temperature gradients near a surface are observed that results in high density gradients. At lower wall temperature ($T_w=1500K$), the profiles of temperature and density near surface are nonmonotone. Temperature has a local minimum on a wall, then it rises in rather thin zone near a surface because of viscous dissipation and a local maximum is forming. Further the temperature is monotonically decreasing to the freestream value $T_\infty=711K$ (Fig. 6.a). At moderately cold wall temperature $T_w=700K$ that is close to the freestream value, the temperature and density profiles are rather uniform. The solution obtained for “cold” temperature ($T_w=300 K$, line 1) that is typical conditions for experiments in short-duration facilities diverges drastically from all others. The main discrepancies are related to the lower temperature and the higher density the recirculation zone and the larger extent of the separation.
Section VI

The next section S2 is located in a middle part of the separation zone. A weak influence of $K_T$ can be seen on profiles of mean velocity in the mixing layer (ML) located at $0.5 > y/h > 0.9$ (Fig.7.c). It must be mentioned that for $T_w=300K$ the mixing layer is located higher than that at another $T_w$ values. Above the mixing layer, an expansion fan (EF) is disposed. The section $x=\text{const}$ passes EF in an "inverse" direction, i.e. from lower to higher pressure. Inside the recirculation zone, an essential distinction in the temperature and density profiles is observed (Fig. 7. b.). The profiles of temperature in separation zone and a mixing layer for various $T_w$ are different. The turbulent kinetic energy profiles have three local maximums, the first is in reverse flow, the second is on a dividing streamline and third is in the central part of mixing layer (Fig. 7. d).
The S3 section is located in the reattachment region (Fig. 8). The recirculation zone is narrow: $0.3 > y/h > 0$ and the expansion fan is closer to a body surface: $2.0 > y/h > 1.1$. For $T_w = 300K$ the vertical size of recirculation zone is larger than those at other $T_w$ values (Fig. 8. c). For adiabatic and moderately cold $T_w$ values, the large temperature gradient exists at a border between the mixing layer and therecirculation zone. For case of $T_w = 300K$, the temperature distribution is uniform in S3 cross-section.

![Figure 8](image1.png)

**Fig. 8.** Temperature (a), density (b), velocity (c) and turbulent kinetic energy (d) profiles S3 section.

The comparison of computed density fields and experimental Shadow picture for $M=3.5$ is shown in Fig.9. The computations predict all the wave flow structures like EF, TSW and sizes of recirculation zone RZ. It must be mention that two-vortex structure of RZ can easily be seen in computed picture by streamline pattern and in experimental picture by dark line deviated two vortexes.

![Figure 9](image2.png)

**Fig. 9.** Computed density field and experimental shadowgraph at $M_\infty=3.5$
Conclusions

The computation studies have been performed to investigate the influence of the temperature factor on the parameters of supersonic turbulent flows in vicinity of BFS at Mach numbers \( M_\infty = 2 \div 3.5 \) and wide range of wall temperature: from adiabatic to cold \( T_w = 300 \text{ K} \). It is shown that wall temperature conditions effects strongly on all the flow parameters in vicinity of BFS. With \( T_w \) decreasing, base pressure behaves nonmonotonically.

Under the adiabatic temperature condition, the three-vortex structure has been observed with small clockwise vortex in the inner corner, rather big counterclockwise middle vortex and the clockwise vortex adjusted to the external flow. When temperature of the wall is decreasing, temperature in the separation region drops, the first vertex disappeared, the second vortex is reduced considerably, and the temperature of recirculation zone is diminishing. With further \( T_w \) decreasing, the three-vertex structure is re-established with temperature of the whole separation region close to the temperature of the wall. The analysis of gas-dynamical and turbulent parameter profiles has shown the significant difference of the flow regimes under various temperature conditions.

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REFERENCES