Effect of Mach and Reynolds numbers on the parameters of the high-pressure layer in the supersonic separated flow near a ramp

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Abstract. Results of a study of the structure of a supersonic separated flow formed in the vicinity of a compression ramp are reported. At high supersonic speeds, a thin high-pressure layer may form in the re-attachment zone over the inclined wall of the ramp. The gas-dynamic quantities in such a high-pressure layer can noticeably differ from the flow quantities in the surrounding stream. The influence of Mach number (in the range of M = 3–8) and Reynolds number (laminar or turbulent mode of separation) on the flow structure is studied, and the occurrence possibility of the high-pressure layer is analyzed.

1. Introduction

A supersonic separated flow in the vicinity of a compression ramp can be realized with the formation of a thin layer in re-attachment zone (figure 1, the layer is designated as HTL) whose flow quantities considerably differ in magnitude from the quantities in the surrounding stream [1–3]. For example, it was found that the total pressure in the thin layer with laminar separated flow at M = 6 could reach 0.95 of the total-pressure value in the free stream. This thin layer arises directly near the re-attachment line and is located over the boundary layer formed by the inclined surface of the ramp.

Also, figure 1 shows: the compression shocks C1 (shock due to the leading edge of the model), C2 (shock due to the flow separation process), and C3 (shock due to the flow re-attachment process); the shear layer SL detached from the model; and the zone of reverse flow RF. The line of flow separation is designated as S, and the line of flow re-attachment, as R.

The absence in the literature of a description of such flows points to the necessity of studying the conditions under which the formation of the high-pressure layer of interest becomes possible. In [4], it was shown that the high-pressure layer could form at M = 6 on a model whose range of ramp angles was φ = 20 – 50°.

In the present work, we analyze the impact of Mach number (in the range of M = 3 – 8), Reynolds number (Re = 0.3·10^6 – 5.4·10^6), and the flow regime (laminar or turbulent) both on the structure of the separated flow and on the presence or absence of the high-pressure layer in the system under study.
2. Experimental procedure

The experiment was carried out in the T-326 and T-333 wind tunnels of ITAM SB RAS. Both Schlieren visualization of the flow and its probing with a total-pressure probe on the surface of the model were performed.

The influence due to Mach and Reynolds numbers was studied using a model ramp (figure 2) with ramp angle $\varphi = 30^\circ$. The width of the model was equal to the distance $L$ from the leading edge of the model to the line of joint of the horizontal and inclined surfaces of the ramp ($L = 50$ mm). The leading edge of the model was sharp, with the radius of its curvature being equal to $R \sim 5\,\ldots\, 10 \,\mu\text{m}$.

The Mach number varied in the range $M = 3 \ldots 8$. The Reynolds number based on the length of the horizontal part of the model $L$ varied in the range $Re = 0.3 \cdot 10^6 \ldots 5.4 \cdot 10^6$, which values have allowed us to realize both laminar and turbulent modes of separation. For achieving a high Reynolds number, part of the experiments was performed without heating the air in the wind-tunnel prechamber. In the latter case, for Mach numbers $M = 5$ and $6$ a flow with air condensation in the wind-tunnel test section established. The regimes of flow separation at $M = 6$ and $Re = 1.9 \cdot 10^6 \ldots 5.4 \cdot 10^6$ can be transitional ones from laminar to turbulent mode. The flow at $M = 6$ and $Re = 5.4 \cdot 10^6$ without heating (or, in other words, with air condensation) was close in its structure to the turbulent flow.

The numerical calculations were performed using the Fluent software package. The calculated data were verified by means of their comparison with experimental data.

Three-dimensional Navier–Stokes equations or turbulent Reynolds equations in stationary statement were solved using a differential two-parameter k-\omega SST model of turbulence. The solution of Navier–Stokes equations has allowed us to simulate the laminar separated flow past the model at Mach numbers $M = 6 \ldots 8$ ($Re = 0.6 \cdot 10^6 \ldots 5.3 \cdot 10^6$), and the solution of Reynolds equations, at Mach
numbers $M = 3 - 6$ ($Re = 0.6 \cdot 10^6 - 2.4 \cdot 10^6$). The working medium was perfect gas (air), whose heat capacity was assumed constant. The thermodynamic state of the gas was described using the Mendeleev–Clapeyron equation. The molecular viscosity was calculated using the Sutherland formula, and the thermal conductivity, using the Aiken formula. Possible condensation of air was disregarded.

The geometry of the compression ramp in the calculations was the same as that of the experimental model. In the calculations, the walls of the model were assumed non-heat-conducting.

At the inlet and lateral boundaries of the computational domain, the Mach number, the static pressure, and the static temperature were specified. At the outlet boundary, reference values of static pressure and stagnation temperature were posed. For a turbulent flow, the value of turbulence intensity ($I = 0.5\%$) and the ratio between the coefficients of turbulent and molecular viscosity ($\mu_t/\mu = 1$) were set.

In various cases, the computational domain contained a total of 5 to 9 million cells, all of these cells being structured into blocks. Near the wall, the grid was made condensing for adequate resolution of the near-wall flow (the boundary layer in front of the separation line and the shear flow behind the re-attachment zone). The problem was solved by the relaxation method with second-order accuracy in approximating the derivatives in conservation equations and with first-order accuracy of such approximation in transport equations used for calculating the turbulence parameters.

3. Results

Because of the absence of lateral walls on the model, which would prevent the downward gas flow through the lateral boundaries of the zone of reverse flow, the separated flow is a three-dimensional one. Figure 3, (a) (at the top) shows a schlieren photograph of the turbulent separated flow with $M = 3$. The calculated distribution of limiting streamlines drawn from the shear-stress vectors on the ramp surface is shown below. A similar picture is observed in the case of laminar separation occurring at $M = 6$ (figure 3, (b)). Evidently, there exists a good qualitative agreement between the calculated and experimental data, allowing one to use numerical results for analyzing the structure of the flow in the re-attachment zone.

![Figure 3](image)

**Figure 3.** Structure of the separated flow in the vicinity of the compression ramp (at the top - schlieren photograph (experiment), at the bottom - the calculated distribution of limiting streamlines on the surface of the model): (a) $M = 4$ (turbulent mode), (b) $M = 6$ (laminar mode).
The presence of curvilinear lines of flow separation and re-attachment points to a complex 3D structure of the flow in the separation region, in which the gas in the zone of reverse flow moves not only against the free stream but, also, toward the lateral boundaries of the model.

Figure 4 shows schlieren photographs of the turbulent separated flow in the range of Mach numbers $M = 3–6$ and Reynolds numbers $Re = 3.1 \cdot 10^6–5.4 \cdot 10^6$. At $M = 5$ and $M = 6$, the experiment was conducted without heating the air, which led to the condensation of the nitrogen and oxygen contained in the air, and the flow regime was not strictly turbulent.

Figure 5, (a) shows a diagram of the separated flow in the plane of symmetry for the range of Mach numbers $M = 3–6$ drawn according to the calculated data (turbulent flow regime) and the results of schlieren visualization of the flow in the vicinity of the model. Figure 5, (b) shows the calculated distribution of the total pressure $p_0/p_0\infty$ in the section $l/L$ along the normal coordinate $r/L$ for the cases illustrated by figure 5, (a). Here, $l$ is the longitudinal coordinate parallel to the surface of the model, $r$ is the coordinate normal to the surface, $p_0$ is the total pressure in the section under consideration, and $p_0\infty$ is the total pressure in the free stream.

Evidently, with increase in the Mach number the angle of inclination of all shocks to the horizontal plane decreases in value, the losses of the total pressure behind the $C_3$ compression shock show an increase, and the height $r_{CF}$ of the fan of compression waves over the surface of the model shows a decrease. At Mach number $M = 3$, the losses of total pressure in the flow having passed the separation shock $C_2$ and the compression fan $CF$ are relatively low, and the height of the fan $r_{CF}$ almost reaches the point of interaction of the separation shock $C_2$ and re-attachment shock $C_3$. As a result, the whole gas stream between the boundary layer BL and the slipstream SS remains a high-pressure one. As the Mach number increases from $M = 4$ to $M = 5$, the losses of total pressure in the region between BL and SS grow in value, and there appears a distinct maximum of total pressure $p_{0\text{max}}$.

At $M = 6$, the CF is pressed to the model surface, and the losses behind the $C_3$ shock become even more pronounced. As a result, a thin layer of high-pressure gas — a high-pressure layer — forms near the wall of the model ramp over the boundary layer. The obtained data suggest that a high-pressure layer can be formed at Mach numbers $M > 5$.  

![Schlieren photographs of the separated flow](image.png)

**Figure 4.** Schlieren photograph of the separated flow at $M = 3–6$.


Figure 5. Schematic of the separated flow (a) and the profile of total pressure (b) in the cross-sections \( l/L = 0.4 \) (M = 3, 4), \( l/L = 0.45 \) (M = 5), and \( l/L = 0.5 \) (M = 6).

Figure 6. Schlieren photograph of the separated flow at M = 6 – 8.

Figure 7 shows the measured Pitot-pressure profiles (the Pitot pressure is the total pressure in subsonic flow and the total pressure behind a normal shock in supersonic flow) in the cross-sections \( l/L = 0.35 \) (for M = 6, figure 7, (a)) and \( l/L = 0.3 \) (for M = 8, figure 7, (b)). Local maxima (designated as HTL) indicating the presence of a wall layer with a high total pressure are distinctly seen.

Two profiles obtained in different experiments are shown in figure 7, (b). The difference in the maxima of total pressure in the HTLs illustrates the effect due to the near-wall longitudinal vortexes of the Görtler type on the parameters of the high-pressure layer.

The results show that in the case of laminar separated flow with M = 6 and M = 8 the high-pressure layer can be identified throughout the entire range of Reynolds numbers studied \((0.3\cdot10^6 - 2.9\cdot10^6)\). The height of the layer over the surface of the model and its intensity both decrease slightly with increasing the Reynolds number. The effect due to air condensation on the formation of the layer is weak.
Figure 7. Profiles of Pitot pressure in the cross-sections $l/L = 0.35$ ($M = 6$) and $l/L = 0.3$ ($M = 8$).

4. Conclusion
The reported results of the performed study of the gas flow structure in the re-attachment zone of the 3D supersonic separated flow formed in the vicinity of a ramp made it possible to identify conditions for the occurrence of the high-pressure layer.

A necessary condition is a high velocity of the free stream ($M > 5$). The impact of the regime of the flow (laminar or turbulent) and the impact of air condensation on the formation process of the layer are less pronounced.

A high-pressure layer was found to exist on the model with a ramp angle of 30° in the range of Mach and Reynolds numbers $M = 6 – 8$ and $Re = 0.3 \cdot 10^6 – 2.9 \cdot 10^6$ for the laminar regime, and $M = 6$, $Re = 5.4 \cdot 10^6$ for the turbulent regime. The absence of this layer at $M = 3 – 5$ and $Re = 3.1 \cdot 10^6 – 5.3 \cdot 10^6$ is shown.

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