Effect of side walls on the supersonic ramp flow structure

L P Trubitsyna, V I Zapryagaev and I N Kavun
Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, 4/1, Institutskaya str., Novosibirsk, 630090, Russia
lukeria.trubitsyna@gmail.com

Abstract. The reattachment zone structure of a supersonic separated ramp flow was experimentally studied at $M_\infty = 6$. Several ramp model configurations with and without side walls were considered. It was found that the geometric size of streamwise vortices in the reattachment zone increases due to the absence of transverse flow in the separation region. Moreover, flow separation regions were detected on the model side walls which interact with the ramp-induced separation region, forming corner vortex structures.

1. Introduction

The features of a supersonic separation flow (such as streamwise vortex structures in the reattachment zone or shock wave-boundary layer interactions) can lead to heavy local thermal and power loads on the aircraft surface. Review papers [1] and [2] consider the main types of separated flows, their features, numerical characteristics, and the physical formation mechanism. Streamwise wall vortices arising in the reattachment zone of a supersonic separated flow are described in [3]. Review paper [4] examines the structure and gas-dynamic characteristics of such vortices.

Figure 1. The surface-adjacent ramp flow: a – oil flow visualization of limit streamlines, b – streamlines obtained by averaging numerical calculation data, c – general flow pattern in the separation region; 1 – horizontal plate surface, 2 – ramp surface [7].
The reattachment zone structure of a separated flow at hypersonic freestream velocity \( (M_\infty = 6 – 8) \) was studied in [5] – [7] for a ramp with no side walls. The flow in the separation zone was established to have a three-dimensional mass-flow nature without a single separating streamline surface between the separation line and the reattachment line (figure 1). In this case, the gas continuously flows into the separation region and continuously flows out of it through the side edges of the model (figure 1, (c)). An intensive flow is established inside the reverse flow region both towards the flow and in the transverse direction from the midline to the side edges of the model.

The authors of [9] consider the supersonic separation flow on a similar ramp model with installed side walls at the Mach number of \( M_\infty = 6 \). This work shows the existence of corner streamwise wall vortices and analyses the heat flux distribution on the model surface which was not done in [5] – [7]. The flow structure was not however compared to the case of a ramp model without side walls. Meanwhile, the flow structure in the reattachment zone can change in presence or absence of the lateral flow, and the magnitude and spatial distribution of the gas-dynamic parameters in it can vary significantly, therefore, analysis of this effect is an important fundamental problem.

2. Experimental techniques

The reattachment zone flow for a ramp model with installed side walls was studied experimentally. Three ramp models were studied, all sizes were the same except for the ramp angle \( \phi \) which was 20°, 30° and 40°. The horizontal plate length was \( L = 50 \) mm, the model was equal to the horizontal plate length, and the curvature radius of the sharp leading edge was \( R = 5-10 \) \( \mu \)m. Freestream Mach number was \( M_\infty = 6 \), and Reynolds number calculated by the length of the horizontal plate was \( \text{Re}_L = 6.1 \cdot 10^5 \).

The experiments were carried out in T-326 hypersonic blowdown wind tunnel in the Khristianovich Institute of Theoretical and Applied Mechanics in Novosibirsk.

The experiment included surface oil flow visualization, Schlieren visualization of the flow using IAB-451 shadowgraph instrument, and surface temperature visualization using a Seek Thermal Compact thermal imager. In addition, the Pitot pressure distribution was measured behind the reattachment line above the ramp surface using a Pitot probe (figure 2). The angle between the probe axis and the model surface is 5–10 degrees so that the probe mount frame does not disturb the near-wall flow. The height and width of the probe tip are 0.2 and 1.1 mm, respectively; the measuring hole has a height of 0.07 mm and a width of 0.8 mm. The probe can be positioned with an error of max \( \pm 20 \) \( \mu \)m along any of the coordinate axes by a 3D traverse gear. The Pitot pressure is measured in the transversal direction along the \( Z \)-axis over the entire model width at several distances \( l \) from the plate-ramp joint \( O \).

![Figure 2. Experimental setup.](image-url)
Studying the flow by independent methods (since visualization is a non-contact technique and probing is a contact technique) enabled to increase the overall validity of the study and mutually complement the results obtained by these methods.

3. Results and discussion

3.1. Surface flow visualization

Figure 3 presents the results of the surface oil flow visualization for the 30° ramp model without side walls (a) and with them (b). Evident that for the model with side walls the separation line S moves toward the leading edge and the reattachment line R – toward the ramp end. The period of streamwise vortex structures in the reattachment zone increases (from 2–3.5 mm for the ramp without walls to 4.5–10 mm for the ramp with walls).

![Figure 3](image)

Figure 3. Surface oil flow visualization for the 30° ramp model: a) without side walls; b) with side walls.

Figure 4 presents the temperature distribution for the 30° ramp model without side walls (a) and with them (b). The temperature distribution pattern qualitatively agrees with the data of the surface oil flow visualization.

![Figure 4](image)

Figure 4. Temperature distribution for the 30° ramp model: a) without side walls; b) with side walls.

3.2. Flow structure on the model side walls

Figure 5 shows the results of the surface oil flow visualization and Schlieren visualization for the 30° ramp model. To carry out the Schlieren photography, the model was equipped with transparent glass.
walls. Evident that, in addition to the main separation region S formed by the ramp, symmetrical separation regions V appear on the side walls of the model (the dark region in figure 5, (b), marked by a dashed line, shows the absence of gas flow along the wall, which indicates a reverse flow zone). The streamlines on the model surface at the boundaries of the separation regions V (figure 5, (c)) show the interaction between them and the main separation region S with the forming corner streamwise vortices described in [8].

![Figure 5](image)

**Figure 5.** Flow structure visualization for a 30° ramp model with side walls: a) Schlieren flow visualization; b) surface oil flow visualization, side view; c) surface oil flow visualization, top view. S - ramp–induced separation zone, V - corner separation zone

The similar flow pattern is observed for the 40° ramp model (figure 6). The boundaries of the separation regions V have a larger inclination angle compared to figure 5, which may indicate an increase in the corner interaction intensity.

![Figure 6](image)

**Figure 6.** Flow structure visualization for a 40° ramp model with side walls: a) surface oil flow visualization, side view; b) surface oil flow visualization, top view.

3.3. *Transversal Pitot pressure distribution behind the reattachment line*

The Pitot pressure was measured behind the reattachment line in the transverse direction. Figure 7 shows the Pitot pressure distribution for models with a ramp angle of $\phi = 20^\circ$ and $30^\circ$. The geometric size and
the period of streamwise vortex structures increase in the case of the model with walls which is confirmed by the visualization data.

Figure 7. Transversal Pitot pressure distribution for the ramp model with and without side walls: a) 20° ramp model measured 23 mm from the plate ramp joint; b) 30° ramp model measured 25 mm from the plate ramp joint

4. Conclusions
The comprehensive experimental study of the reattachment zone structure was conducted in a supersonic separated ramp flow in the presence of side walls. Due to the absence of the lateral flow, the geometric (transverse) dimensions of the streamwise vortex structures behind the reattachment line increase. Moreover, the flow separation regions were detected on the model side walls which interact with the ramp-induced separation region, forming the corner vortex structures.

Acknowledgements
This work was partially supported by the Program of Fundamental Scientific Research of the state academies of sciences in 2013-2020 (project No. AAAA-A17-117030610137-0) and by the Russian Foundation for Basic Research (project No. 19-31-90035).

The study was conducted at the Joint Access Center “Mechanics” of ITAM SB RAS.

References
[1] Chang P K 2014 Separation of flow (Elsevier)
[2] Babinsky H and Harvey J K 2011 Shock wave-boundary-layer interactions vol 32 (Cambridge: Cambridge University Press.)
[3] Ginoux J J 1971 AIAA Journal 9 759-60
[4] Borovoy V Ya 1983 Techenie gaza i teploobmen v zonah vzaimodejstvia udarnyh voln s pogranichnym sloem (Moscow: Mashinostroenie) (in Russian)
[5] Zapryagaev V I, Kavun I N and Lipatov I I 2014 Fluid Dynamics 49 819-26
[6] Zapryagaev V I and Kavun I N 2016 TsAGI Science Journal 47 27-36
[7] Kavun I N, Lipatov I I and Zapryagaev V I 2019 International Journal of Heat and Mass Transfer 129 997-1009
[8] Chuvakhov P V, Borovoy V Y, Egorov I V, Radchenko V N, Olivier H and Roghelia A 2017 Journal of Applied Mechanics and Technical Physics 58 975-89