Investigation of turbulent boundary layer separation on the heated ramp surface

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Abstract. The separation of the turbulent boundary layer in the supersonic flow was studied by means of the particle image velocimetry method. The influence of the wall temperature and the geometry conditions on the separation instability was investigated. The averaged velocity vector fields have shown that the growth of the separation length increases the reattached boundary layer thickness. The root mean square velocity fields have shown that the amplitude of the separation boundaries oscillation strongly depends on the wall temperature conditions and weakly depends on the size of the separation bubble.

1. Introduction
A boundary layer separation occurs, when a pressure gradient reaches its critical value. That usually happens in a presence of shock structures. For example, in the case of a compression ramp an oblique shock is a source of the pressure gradient, which is transferred upstream in a subsonic part of a boundary layer. The separation of the incoming boundary layer causes a formation of a separation bubble, which consists of a recirculation region and a shear layer above it. The recirculation region starts at the separation position and ends at the reattachment position of the boundary layer. The boundary layer becomes the shear layer after its detachment. The shear layer spreads until the reattachment position, where it becomes the boundary layer again. The shear layer carries mass and momentum fluxes from a supersonic external flow to the subsonic recirculation region. Therefore, the length of the shear layer is a very important characteristic. It is called a separation length $L_{sep}$. The separation length is defined as a distance between the position, where the separation begins, and the position of the boundary layer reattachment. The separation bubble causes separation and reattachment shocks. A separation shock foot (a part near the sonic line of the boundary layer) oscillates across an area inside the boundary layer, which is called an intermittent region. Processes, which take place inside the intermittent region and the shear layer, influence the external flow and the reattached boundary layer.

The turbulent boundary layer separation is a non-stationary phenomenon. Due to its complexity, the separation of the boundary layer can be characterized by a wide range of frequencies. The most intriguing is a low-frequency unsteadiness of the separation boundaries. A considerable amount of research studies was devoted to reveal basic principles of this phenomenon. There are two theories that explain the low-frequency separation unsteadiness. First one claims that the fluctuation of the separation boundaries is due to coherent structures in the incoming turbulent boundary layer [1]. These structures interact with the separation shock...
foot inside the intermittent region and cause the low-frequency fluctuation of the separation bubble edges. Another theory associates the low-frequency fluctuations with coupling mechanism of the shock wave and the fluid inside the separation bubble [2]. It was suggested that the shear layer entrains the low-momentum fluid in the separation bubble and creates a deficit of mass inside the separation region. The average mass of the fluid inside the separation region should remain constant so the separation bubble has to recharge its mass [3]. According to this theory, the separation length, which is the length of the shear layer, is an important characteristic of the reattached boundary layer disturbance and the separation bubble oscillations. At the present moment, each of these theories has been proved by experiments and numerical simulations, but it is still unclear, which of these mechanisms makes dominating contribution to the low-frequency unsteadiness of the boundary layer separation.

The main goal of the present work is to understand, which of the processes described above is the main source of the boundary layer separation unsteadiness. The current research was devoted to an experimental investigation of a shock-wave turbulent boundary layer interaction on a heated ramp surface. It was found that a heat transfer affects the boundary layer coherent structures [4]. The simulations have shown that an increase of the boundary layer temperature diminishes a size of the coherent structures. In addition, a heating of the boundary layer leads to an increase of the separation length. Therefore, the heating of the boundary layer helps to compare the influence of the coherent structures and the coupling mechanism on the separation bubble oscillations.

2. Experimental setup

The experiments were conducted in a supersonic wind tunnel, which generates a flow with the following parameters:

- Mach number $M = 2$ (corresponds to velocity of 520 m/s);
- static pressure of supersonic jet $p_{st} = 0.15$ atm.

The boundary layer separation was formed on the compression ramp with angles of $23^\circ$ and $30^\circ$. The ramp surface consists of two steel plates. One plate was aligned parallel to the external flow. Another plate was aligned at $23^\circ$ or $30^\circ$ angle to the external flow. The ramp surface was heated by an electrical chain inside it. A surface temperature was measured by 5 thermocouple elements, which were placed streamwise at the middle of the plates.

For the flow visualization purposes the particle image velocimetry (PIV) technique was used. The PIV principle is based on seeding a flow with small particles. The particles are visualized by means of a laser sheet and recorded on a camera. A displacement of particles is calculated by a cross-correlation algorithm. The particles displacement divided by the time interval between successive picture frames yields a velocity vector field of the flow. The size of the particles has a strong influence on the PIV accuracy. The particles should be big enough to reflect an appropriate amount of the laser light and in the same time they should be small enough to follow the flow. An oil spray with the particle size of $\approx 1 \mu m$ was used in the current PIV experiments. This size of the oil droplets was found to be optimal for gas flow investigations. Unfortunately, in a presence of strong velocity gradients (shock waves) the particles always fail to follow fast changes of the fluid velocity. This effect is called a particles relaxation. It leads to an unavoidable smearing of shock wave edges in the velocity vector field. The smearing of the shock wave decreases a spatial resolution of a shock wave area, so the particles relaxation effect had to be taken into account. In the present studies the particles relaxation yielded an ambiguity of the shock wave area of $\approx 3$ mm, while the spatial resolution of the rest area was 1 mm.
Figure 1. The averaged velocity field for $T_w/T_\infty = 2$ (a) and 1.6 (b); the ramp angle is $23^\circ$ (a) and $30^\circ$ (b).

Figure 2. The RMS velocity field for $T_w/T_\infty = 2$ (a) and 1.6 (b); the ramp angle is $23^\circ$ (a) and $30^\circ$ (b).

3. Experimental results

The velocity vector fields of the separation region were obtained for different wall temperature conditions. The temperature condition was described by a temperature ratio parameter $T_w/T_\infty$, where $T_w$ is the temperature of the surface and $T_\infty$ is the temperature of the external flow. The wall temperature condition was altered in the range of 1.6–3.11 during the experiments. The temperature ratio of $T_w/T_\infty = 1.6$ corresponds to an adiabatic wall. A set of 150 experiments for each temperature condition was conducted, and instantaneous velocity vector fields were obtained by means of the PIV. Thus, the averaged velocity fields and the root mean square (RMS) velocity fields were calculated (figures 1 and 2).

The averaged velocity fields were used to measure the incoming and the reattached boundary layer thickness, which is the characteristic of a boundary layer disturbance. Though vortex structures and small-scale velocity fluctuations disappear after averaging over a large number of instantaneous pictures, they still contribute in a boundary layer profile and a boundary layer
thickness. An increase of a boundary layer disturbance leads to a growth of the boundary layer thickness. For the adiabatic wall the reattached boundary layer thickness normalized on the incoming boundary layer thickness was $\approx 3.2$ and $\approx 4.8$ for $23^\circ$ and $30^\circ$ ramps, respectively. The separation length $L_{sep}$ was 13 mm and 17.7 mm for $23^\circ$ and $30^\circ$ ramps, respectively. In the case of the heated surface, the boundary layer thickness increases with the temperature ratio for both ramp angles. A comparative analysis of the separation on $23^\circ$ and $30^\circ$ ramps has shown that for the equal separation length the normalized thickness of the reattached boundary layer has almost the same value of $\approx 4.8$ (see figure 1). Therefore, the thickness of the reattached boundary layer depends mainly on the separation length, which means that there are the processes inside the shear layer, which determine the boundary layer disturbance after the reattachment.

The RMS velocity fields have shown regions of a velocity perturbation (see figure 2). According to the RMS velocity fields, the largest perturbed area is at the separation position. The reattachment region also has the strong velocity perturbation. These regions are related to the bubble boundaries oscillation. For both $23^\circ$ and $30^\circ$ ramps increasing the temperature ratio causes a prolongation of the perturbed regions. In the case of $23^\circ$ ramp the oscillation area for $T_w/T_\infty = 2$ was found to be 1.5 times larger than for the adiabatic wall condition. A comparison of the RMS velocity fields for $23^\circ$ and $30^\circ$ ramps has shown that for the equal separation length the separation bubble formed on the $30^\circ$ ramp is more perturbed. The theory of the coherent structures described above can explain this effect. The ramp with $23^\circ$ angle had the higher temperature ratio during the experiment, see figure 2(a), so the incoming boundary layer for $23^\circ$ ramp was more heated than the boundary layer for $30^\circ$ ramp. Taking into account that the heating diminishes the size of the coherent structures [4], one can conclude that the heating of the boundary layer also diminishes the oscillation of the separation bubble. Therefore, according to the experiment (see figure 2), the coherent structures mechanism plays the major role in the separation bubble oscillation.

4. Conclusion
The wall temperature influence on the separation of the turbulent boundary layer was investigated. The velocity vector fields of the boundary layer separation on the heated ramp were obtained. The experimental results have shown that the heating of the ramp surface increases the separation unsteadiness for the certain ramp angle, but the heating itself decreases the oscillation of the separation bubble. Therefore, the current experiments have proved that it is the mechanism related to the coherent structures, which has the major influence on the bubble oscillation. At the same time, it has been shown that the processes in the shear layer are responsible for the reattached boundary layer disturbance.

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