Investigation of shock wave-boundary layer instability on the heated ramp surface

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Abstract. By means of particle image velocimetry method shock-wave boundary layer interaction on the pre-heated ramp surface was investigated. The influence of surface heating on separation region unsteadiness was proved. It was found experimentally that increasing of wall to outer flow temperature ratio raises amplitude of separation region oscillation.

1. Introduction
Shock wave-boundary layer interaction (SWBLI) is an unsteady phenomenon, especially in case of separation region emergence. That unsteadiness of separation region can cause serious control issues when arising on the plane wing [1, 2]. It was found that unsteady behavior of separation bubble contains the low frequencies oscillation [3] (with period \(\sim 0.0003 \delta/U_0\), where \(\delta\)—boundary layer thickness, \(U_0\)—velocity of outer flow). That phenomenon still does not have a clear understanding. Though, there are two hypotheses that gives most satisfying explanation of the nature of these oscillation. First one declares that low frequencies oscillation are caused by the coherent structures presented in the incoming boundary layer [4]. Another one explains oscillation using coupling mechanism of oblique shock wave interaction with separation bubble [5].

Heating of incoming boundary layer increases instability of boundary layer and can affect the coherent structures [6]. If the first hypothesis is correct, rising wall temperature will affect the separation region oscillations [7]. Current work is aimed to study the interaction of shock wave with turbulent boundary layer on the heated ramp surface. Investigation of SWBLI unsteadiness on the heated surface is able to clarify the nature of low frequency oscillation of separation region.

2. Experimental setup
Supersonic vacuum wind tunnel ST-4 was used in the current experiments. It generates supersonic flow with the following parameters:

- Mach number \(M = 2\) (Velocity of 520 m/s),
- static pressure of supersonic jet \(p_{st} = 0.15\) atm.

Ramp was placed inside the working chamber of the wind tunnel at the outlet of the de Laval nozzle. The ramp model includes two steel plates mounted angle-wise to one another on special mounts. The first plate surface is parallel to the nozzle symmetry axis and the other plate is positioned at some angle (called ramp angle below) to the incoming flow.
Figure 1. The scheme of PIV visualization. 1—the high pressure vessel, 2—reducer, 3—particle generator, 4—pneumatic valve, 5—de Lavale nozzle, 6—camera with power unit, 7—laser sheet forming optics, 8—chamber window, 9—ramp, 10—working chamber, 11—laser, 12—vacuum lock, 13—vacuum lock drive, 14—gasholder, 15—laser power unit, 16—computer and Programmable Time Unit (PTU), 17—LATRs.

For visualization particle image velocimetry (PIV) was used [8]. PIV principle consists in displacement measuring of the small particles (oil spray in current experiments) seeded into the flow. Based on measurements of particles’ displacements the velocity vector field of the flow is calculated. Figure 1 shows the scheme of PIV visualization. Particle generator 3 makes oil spray. The air from the high-pressure vessel 1 passes through the small orifices in the tubes of generator and produce oil spray. Oil particles are seeded in flow before the inlet of de Laval nozzle 5 when pneumatic valve 4 is opened (supersonic tube is working). In the working chamber 10 particles are illuminated by the laser sheet formed by the laser Nd:YAG (Litron Nano L PIV 125-15) 11 and the light sheet optics 7 which consists of a set of turning mirrors and spherical convex and cylindrical concave lenses. CCD-Camera Imager Pro X 2M 6 takes pictures of flow around the ramp 9. Flow images are stored in computer 16 where they are processed by DaVis 7.2 software.

Ramp surface heating was accomplished by three electric elements inside the plates. Position of elements provides uniform heating of the surface. For achieving optimal heating power the elements are connected to the phase through a laboratory autotransformers 17 (LATR) that allows one to vary the voltage from 0 to 250 V. The temperature on the ramp surface is measured by five thermocouples placed along flow direction in the middle of the planes.

3. Experimental results

Velocity vector fields of the supersonic flow were obtained by PIV method. For each case of temperature ratio (ratio of wall temperature to temperature of outer flow $T_w/T_\infty$) 500 instantaneous pictures of velocity vector field for ramp angle of 30 degree were obtained and analyzed. Instantaneous velocity fields have shown that reattached boundary layer contains large-scale vortices not existing in the incoming boundary layer. Instantaneous pictures of velocity field have shown that increasing temperature ratio results in thicker reattached boundary layer. It was not possible to obtain velocity profiles of incoming boundary layer due to not enough magnification of camera. Reattached boundary layer has average thickness $\sim 7\text{mm}$ which allows...
to get velocity profiles near the reattachment area.

Averaged velocity profiles of boundary layer, which were measured at the different distance from reattachment position, have shown that after reattachment boundary layer is perturbed. At some distance from reattachment position, the shape of velocity profile becomes logarithmic. That distance is the recovery length of reattached boundary layer. Experiments have shown that recovery length of reattached boundary layer increases with temperature ratio. According to the figures rising temperature ratio from 1.8 to 3.11 leads to increasing recovery length \( l \) from 4.6 mm to 11 mm (figures 2, 3). Thus, heating of the surface influences on the reattachment of boundary layer.

RMS velocity fields were obtained from 500 instantaneous velocity vector fields. According to the data there are high velocity deviations in the separation region for all spectra of temperature ratios. For \( T_w/T_\infty = 3.11 \) regions of velocity deviations also occur near the reattachment region figure 4. Velocity deviation near separation and reattachment positions reaches 0.38 \( U_0 \).

According to RMS velocity fields, elevating temperature ratio leads to growth of velocity deviation regions located in separation and reattachment positions. That means growth of amplitude of separation and reattachment boundaries oscillations.

Proper Orthogonal Decomposition method (POD) was used to analyze a set of 300 instantaneous velocity fields for each temperature ratio. POD analysis defines main structures of the flow. POD consists in representing of matrix of measurements \( A \) as a product of matrixes \( U, \Sigma \) and \( V^T \). Where \( U \) — orthonormal matrix with temporal modes, \( V \) — orthonormal matrix with spatial modes, \( \Sigma \) is the matrix with singular values of matrix \( A \) that are arranged in descending order. The solution is in finding eigen values \( \lambda \) and vectors of matrix \( AA^T \). Singular value of \( A \) equals square root of corresponding \( \lambda \). Eigen values are also called “energy”. In case of incompressible fluid, eigen values are associated with kinetic energy of fluid, in other cases eigen values has no physical meaning.

According to the POD analysis about \(~60\%\) of whole “energy” is stored in the first 5 spatial modes. That simply means that major flow structures are represented by these modes. The first three modes correspond to motion of separation region. Fourth and fifth modes are the corrections for the first three. In case of the ramp surface with temperature ratio of \( T_w/T_\infty = 3.11 \) first spatial mode contains almost 40\% of “energy” meanwhile in case of adiabatic surface the amount of the “energy” stored in the first mode is only 15\%. This proves that elevation of surface temperature leads to significant amplification of separation region motion.
4. Conclusion
The instability of separation region on the heated ramp surface was investigated by means of PIV and POD analysis. It was found that heating ramp surface has influence on the reattached boundary layer.

RMS velocity fields have shown increasing of amplitude of separation and reattachment boundaries oscillations. This proves that changing temperature ratio affects both on the incoming and reattached boundary layer.

Data analysis, which was made by POD, has shown that rising of temperature ratio has significant impact on the separation region motion.

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