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Study of the transition position on blunted bodies with roughness at $M = 6$

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Abstract. The paper presents the data of the effect of distributed and single roughness on a blunted nose of a cone on the position of the laminar-turbulent transition and the development of perturbations in the boundary layer. The experiments were performed at $M = 5.95$, stagnation temperature $T_0 = 360 \div 418$ K and stagnation pressure $P_0 = 3.5 \div 46$ atm. Unit Reynolds number varied in the range $(4.2 \div 69.7) \times 10^6 \text{ m}^{-1}$. The study was carried out in the boundary layer of a cone with half-angle of 7° with different zones of applying a single and distributed roughness on blunted nose-tip of radii 2 and 5 mm. For all types of roughness, the effective Reynolds numbers corresponding to transition on the model's nose are obtained. The effect of surface roughness on the growth of perturbations in the boundary layer is studied experimentally.

1. Introduction

High thermal loads can initiate the appearance of surface roughness on an aircraft during flight due to ablation of heat-shielding material and surface erosion. Surface roughness can have a significant effect on the distribution of heat fluxes on a hypersonic aircraft, which is mainly caused by the displacement of the laminar-turbulent transition region. The occurrence of roughness on the nose most likely due to the heat load in this area is maximum. The appearance of the transition on a nose usually leads to turbulization of the entire surface of an aircraft [1, 2].

2. Experimental equipment

The experiments were carried out in the hypersonic wind tunnel "Transit-M" of ITAM SB RAS [3] at Mach number of 5.95, stagnation temperature $T_0 = 361 \div 421$ K and stagnation pressure $P_0 = 3.5 \div 46$ atm. Unit Reynolds number varied in the range $Re_1 = (4.2 \div 69.7) \times 10^6 \text{ m}^{-1}$. The diameter of the outlet section of the nozzle was 300 mm, air was used as the working gas.

The influence of roughness on the laminar-turbulent transition in the boundary layer was investigated on a cone with half-angle of 7° and interchangeable noses. The model was made of plastic (polyacetal) to perform thermal field measurements by means of IR-camera and equipped by high-frequency surface pressure sensors PCB 132A31 (see Fig. 1a). Eight pressure sensors were installed along the generating line of the cone, and the 9th sensor was located symmetrically to the 8th on the opposite side to control the angle of attack. The model was installed in the working section at zero angle of attack along the axis of the nozzle and was partially recessed into it. The distance from the trailing edge of the model to the section of the nozzle was 325 mm.



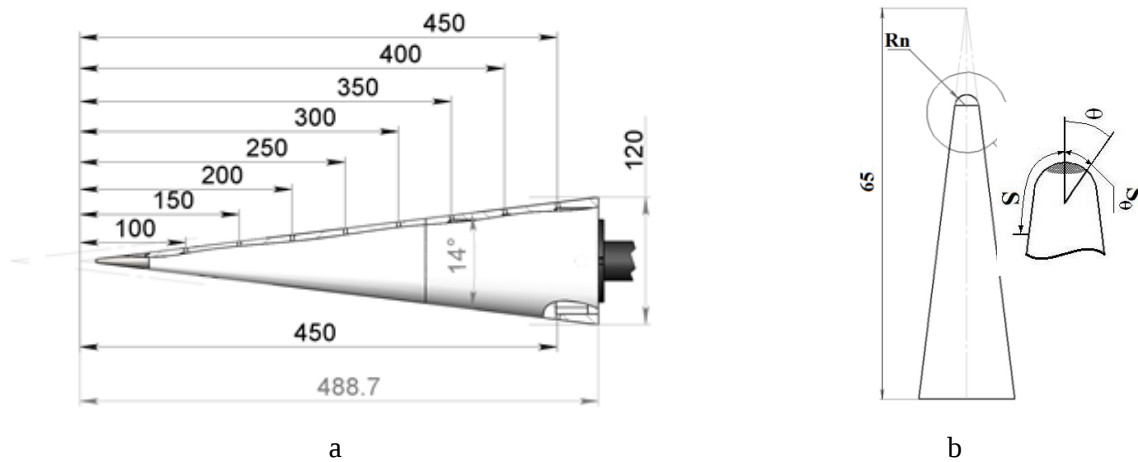


Figure 1. Schematic representation of the model with the location of the surface pressure sensors (a) and enlarged model nose with the designation of the coordinate x and the roughness angle θ ; gray area (S_θ) is sand (b). Dimensions are in millimeters.

The experiments were performed for two types of roughness: distributed (see Fig. 2a) and isolated (see Fig. 2b). The distributed roughness (roughness height $Ra \approx 28$ and $60 \mu\text{m}$ for $Rn = 2$ and 5 mm respectively, where Ra is defined as the standard deviation of surface depressions or bulges from the mean height) was made using two sizes of calibrated sand, pasted onto the nose. Sand was applied at the angle $\theta = 90^\circ$, and then, as necessary, it was cleaned to the desired angle θ (see Fig. 1b). As a material for the production of isolated roughness, a fishing line was chosen which allowed us to control accurately the diameter of roughness.

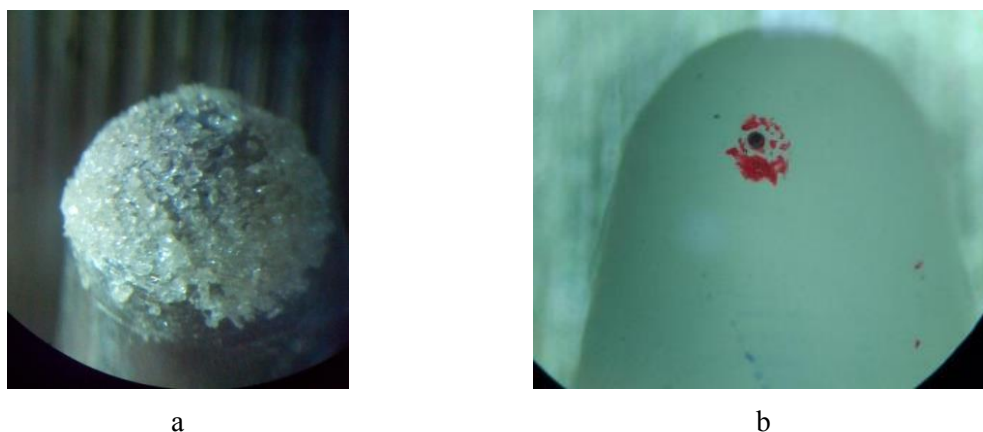


Figure 2. Noses with roughness: a - distributed roughness; b - isolated roughness, nose radius $Rn = 2 \text{ mm}$, roughness height $k = 100 \mu\text{m}$;

Measurements of temperature fields on the surface of the model were performed using a Flir sc7000 thermal imager with a 7300M matrix consisting of 320×256 elements. The temperature range of measurements was $5 \div 150^\circ \text{C}$. The frame rate in the experiments was 250-300 Hz. During the run, the surface of the model was heated by 1 to 2 degrees. To find the magnitude of the unsteady heat flux, the Cook-Felderman algorithm [4] was applied, which makes it possible to obtain a solution to the problem of heat propagation in a semi-infinite body.

Pressure sensors were used in conjunction with the signal converter PCB Piezotronics 482C05. Data were acquired by three ADC L-card E20-10 with a frequency of 1.7 MHz synchronized with the control system. The power spectra were calculated on the basis of discrete Fourier transform. The spectral distributions were calculated by averaging over L blocks of 2^N points in each block in time the period of $95 \div 100$ ms from run beginning. The number of blocks was 65, with the number of points in each of 256.

3. Experimental results

3.1. Distributed roughness

All types of roughness were studied experimentally. The effective values of Reynolds numbers corresponding to transition on the model's nose-tip were obtained. Fig. 3 shows the effective unit Reynolds numbers multiplied by the R_a values for different angles of deposition of the distributed roughness (sand). For both R_n it is clearly seen that with increasing the angle of roughness up to $\Theta = 90^\circ$, the effective Reynolds number decreases. For all investigated radii and angles, this means that the minimum unit Reynolds number at which the transition occurred on the model nose corresponds to the angle $\Theta = 90^\circ$. This result was unexpected. According to the computational study, the most critical location of roughness is near the sonic line ($\Theta \approx 45^\circ$) where Re_{kk} reaches the maximum value [5], i.e. at $\Theta \approx 45^\circ$ Re_{ef} should be minimal. However, as can be seen from the experimental data, Re_{ef} becomes minimal at $\Theta = 90^\circ$.

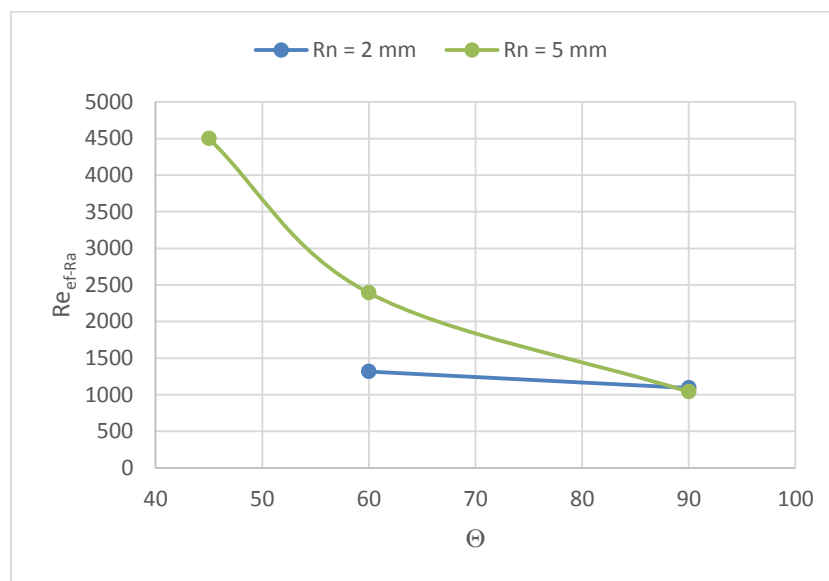


Figure 3. Unit Reynolds number, at which the transition occurred on the nose, multiplied by the average roughness height ($Re_{ef-Ra} = Re_1 \cdot Ra$), vs. of application angle of the roughness Θ .

3.2. Isolated roughness

Fig. 4 shows the difference in the thermal trace along different rays for angle $\Theta = 45^\circ$ for the isolated roughness of height $k = 500 \mu m$ on the nose at $R_n = 5$ mm in terms of Stanton numbers. The line with crosses corresponds to the center line behind the roughness, the line without symbols corresponds to the ray with the maximum heat flux. The transition occurred immediately after the roughness, which is evident from the absence of a minimum along the ray with the maximum heat flux (line without symbols). The figure clearly shows that along the central line there is a local minimum in the heat flux distribution (line with crosses). It was found that formation of two symmetrical vortices or turbulent wakes downstream of the isolated roughness is detected as distribution of heat flux with no minimum

like solid line in Fig. 4. These two turbulent wakes can form two turbulent wedges merging downstream. Such a behavior was observed for all types and angles of the single roughness.

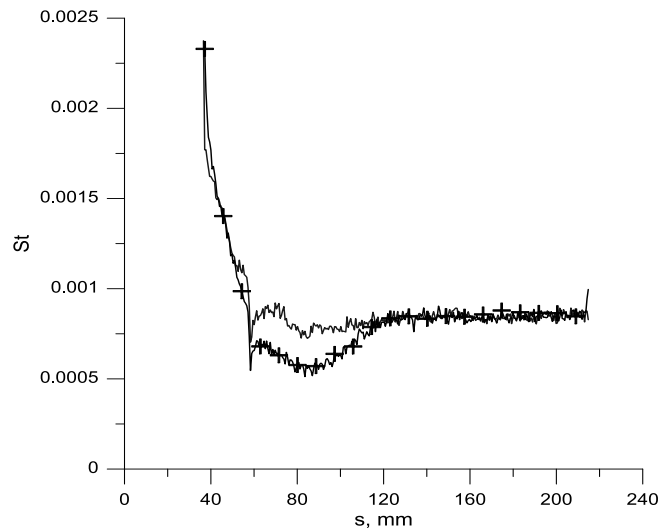


Figure 4. Distribution of Stanton numbers in the wake of the isolated roughness for $Rn = 5$ mm, $k = 600$, $d = 300$ μm , $Re_1 = 36.8 \times 10^6$ 1/m, $\Theta = 45^\circ$.

3.3. The influence of roughness on development of disturbances.

The spectra of surface pressure pulsations were obtained by PCB sensors for each run. Examples of spectra for sensors at $x = 100\text{mm}$ and $x = 250\text{mm}$ are shown in Fig. 5. Fourier amplitude spectra, normalized by the pressure on the edge of the boundary layer, for distributed roughness with the angle of application $\Theta = 90^\circ$, 60° , 45° ; single roughness, standing at $\Theta = 45^\circ$ and smooth nose ($Rn = 5$ mm) are presented.

In the case of the single roughness, the pressure sensors were oriented along the same line as the roughness in order to trace the pulsations in the vortex wake.

Fig. 5a shows that for the roughness at $\Theta = 90^\circ$, the pulsation spectrum of the first sensor ($x = 100$ mm) is completely filled, which indicates the end of the laminar-turbulent transition upstream of the sensor. For the roughness at $\Theta = 60^\circ$ an increase in pulsations is observed over the first sensor (Fig. 5a), which indicates the beginning of intermittency. For the cases of distributed and single roughness with $\Theta = 45^\circ$, the pulsation spectra correspond to a laminar boundary layer. At $x = 250$ mm (Fig. 5b) the spectra for $\Theta = 45^\circ$ are almost filled, which indicates that flow state is close to the end of the transition. Downstream the boundary layer is turbulent for all roughness cases. It is important to note that for the smooth nose-tip the level of pulsations corresponds to the laminar boundary layer, but the roughness leads to the increase in the perturbations level, with no selected frequencies in the spectra (means about perturbations associated with the second mode of Mack).

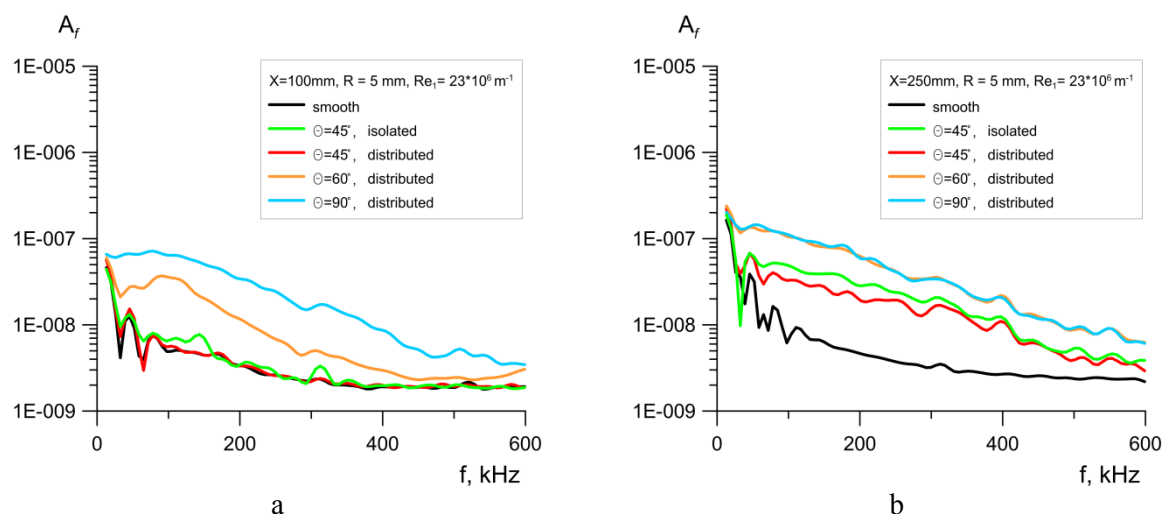


Figure 5. Wall pressure pulsation spectra, $R_n = 5\text{mm}$, $Re_1 = 23 \cdot 10^6 \text{ 1/m}$.

4. Summary

Experimental study was carried out in the hypersonic boundary layer of 7° half-angle cone with different zones of application of the single and distributed roughness on blunted nose-tip with $R_n = 2$ and 5 mm . For all types of roughness, effective values of Reynolds numbers were obtained.

It is shown that for bluntness close to spherical, the most critical location of the roughness is near the conjugation point of the spherical and the conical parts ($\theta \approx 90^\circ$): the unit Reynolds number, at which the transition occurs immediately after roughness formation, is minimum at this location. It was also shown that the presence of roughness significantly influences the growth of perturbations in the boundary layer and can lead to earlier transition.

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