DOI: 10.13009/EUCASS2017-344

Effect of nose-tip roughness on laminar-turbulent transition

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Abstract
The effect of the distributed roughness applied to the blunted nose-tip of the cone on the position of the laminar-turbulent transition is considered. Study is performed at Mach number 5.95. It was found that the position of the roughness plays an important role in the transition process. It was obtained that the roughness has a greater effect on the transition when covers area downstream of the sonic line.

1. Introduction

Different kinds of roughness appears on the nose-tip of the hypersonic vehicle during the process of thermal destruction of the thermal protection coating, which leads to earlier transition. Another important factor affecting the position of the laminar-turbulent transition is the bluntness of the nose or the leading edge of the vehicle. This factor shifts the transition downstream [1-3]. Thus, the presence of a roughness on the blunted nose-tip of the vehicle creates an ambiguous situation: the stabilizing effect of bluntness competes with the destabilizing effect of roughness.
The empirical dependence of the transition position on the nose-tip roughness parameters has been studied in numerous papers [4-6]. Such studies are of great practical importance for aircraft design, but they do not clarify the physics of the transition processes. The study of this phenomenon is a complex multiparameter problem, so obtaining new experimental data on this problem is of great importance.
In the previous work [7] the effect of distributed roughness located on a blunt nose of a conical model on the position of a transition was investigated. In experiments the roughness was uniformly applied to the entire rounding region of the nose-tip. It was found that with an increase of the unit Reynolds number to a critical value, a jump in the position of the transition to the nose of the model was observed.
The current work continues the investigation of the influence of roughness on the stability and transition in the hypersonic boundary layer. In the paper a detailed analysis of the effect of distributed roughness with different application areas is carried out.

2. Experimental setup

The experiments were carried out in the Transit-M wind-tunnel (ITAM SB RAS) at Mach number M = 5.95. Stagnation temperature equalled to T_0 = 360–457 K and stagnation pressure equalled to P_0 = 6.9–43.1 atm. The unit Reynolds number was varied in the interval $Re_1 = (7.7\text{–}65.7)\times10^6$ 1/m. The model was a cone of length 0.45 m with half-angle 7° made of PEEK. The aluminum nose-tip of length 59 mm had a bluntness radius of 2 mm. The model was installed at zero angle of attack. Figure 1 shows a spatial angle θ, which limits a distributed roughness.
Heat-flux measurements on the model surface were carried out using a Flir sc7000 IR camera. In the experiments, the frame rate was 350 Hz. During a wind-tunnel run, the model surface was heated by 1−2 degrees. The unsteady heat flux was determined using the Cook−Felderman algorithm [8].
The experiments were carried out for a sand roughness applied onto the model nose-tip. To determine how much roughness parameters are reproduced, five noses with the same roughness were made. The roughness was selected in accordance with the experiments of the previous work $k_{rms} \approx 30$ μ [7]. Depending on the chosen method, the height *k* can vary by a factor of two or three. In the present study, the height *k* was measured using a 3D Zygo Newview 6300 surface structure analyzer. To determine value of the distributed roughness three parameters were measured: RMS is the standard deviation of the depressions or surface bulges from the midline of the surface; Ra is the standard roughness definition determined as the arithmetic mean deviation of the profile and PV is the largest value in the

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profile deviation (peak-to-peak value). Measurements were carried out in different places of one nose-tip more than ten times. Table 1 shows the measured average roughness parameters for the five noses. For the smooth forebody, the height *k* was about 2 μ .

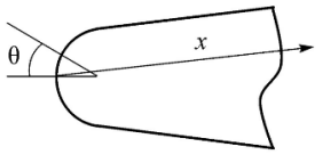
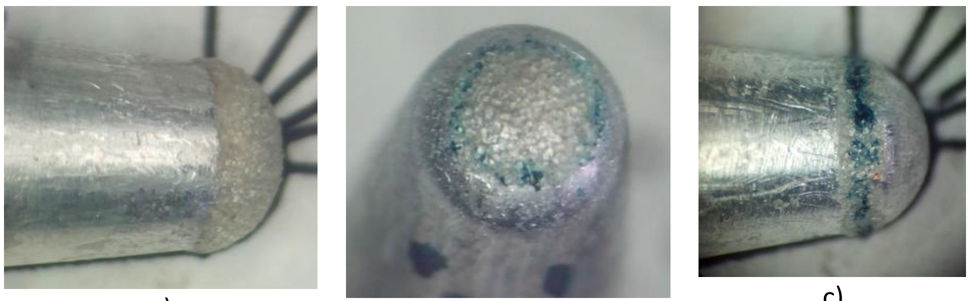


Figure 1: A schematic image of the model nose-tip with definition of Θ and *x*.

Table 1

Number of nose	*Ra*	RMS	PV
1	29	37	263
2	29	37	243
3	23	30	246
4	35	41	250
5	28	34	194



a) b) c)

Figure 2: An example of a sand roughness application to the nose-tip of the model: a) Θ = 90°; b) Θ = 45°; c) is the sand ring (strip) at the angle Θ = 90°.

3. Results

Analyzing the behaviour of X_{tr} and Re_{tr} during the run in a set of runs under different conditions, a time interval was identified in which the transition position is almost not shifted and a good repeatability is observed: 95-105 ms. In this interval, the flow parameters were considered and the transition position was determined.
According to the accepted terminology, the unit Reynolds number effecting the position transition in comparison to the case of a smooth nose-tip is called critical. An effective Reynolds number is the unit Reynolds number at which the transition occurs on the nose-tip of the model. The main aim of the experiments was to find the influence of the position of the distributed roughness on the effective Reynolds number. Here one should note one essential difficulty. In the case of smooth nose-tip the distribution of the heat flux along the width of the model is uniform and the position of the transition does not practically change in width. However, when any type of roughness is applied and at any angle, the flow becomes substantially uneven and the transition line becomes strongly curved along the width of the model (Fig. 3). This feature causes difficulties in comparing the heat flux data and the spectra obtained with the help of sensors. Because usually the heat flux is calculated in one place of the model and the spectra are measured in the other. For the effective Reynolds number determination this feature is not important since if the transition occurs on a nose-tip, then the entire model, as a rule, is flowed by a turbulent flow.
To determine the effective Reynolds number, the unit Reynolds number gradually increased until the transition moved from the tail of the model to the nose. Fig. 4 shows an example of the heat flux distributions on the surface of

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the model for r = 2 mm and roughness area angle θ = 90 ° for several close Re_1. Classical picture of the transition at $Re_1 = 29\times10^6$ 1/m is suddenly changed to the heat flux distribution corresponding to the transition at a nose at $Re_1 = 33\times10^6$ 1/m.

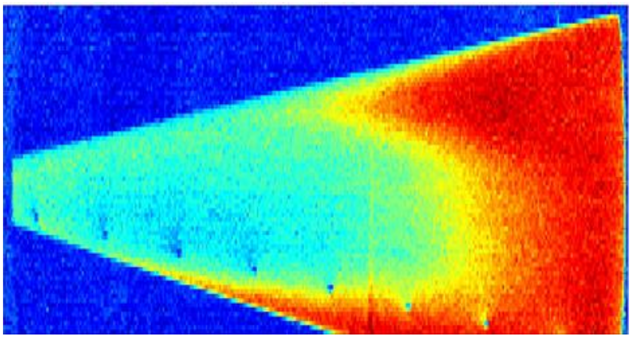

Figure 3: Heat flux field in a presence of roughness on a nose-tip.

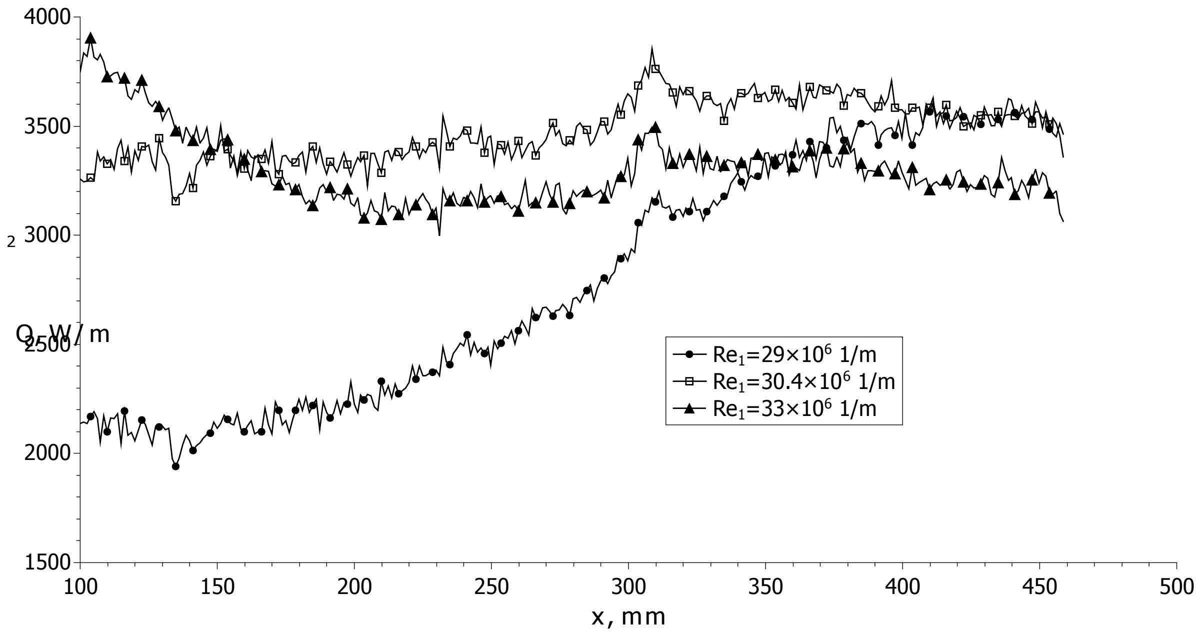

Figure 4: Heat flux distribution on the model surface for three unit Reynolds numbers. r = 2 mm, Θ = 90°.

The effective unit Reynolds numbers for different roughness angles multiplied by the values of Ra and PV are shown Fig. 5. In order to take into account the noses with elongated roughness area (2.5 and 5.5 mm downstream from θ = 90°) the distance from the stagnation point along the generatrix of the cone surface to the roughness boundary s is plotted on the abscissa. The table for the correspondence of the angle θ and s is given in Table 2. Re_{1ef} for a strip of sand is also presented. Two parameters characterizing the roughness (Ra and PV) were chosen because it is still not clear which parameter of the roughness is decisive for the occurrence of a laminar-turbulent transition on a blunted nose. Thera are two points of view: one should take 1) the average value of roughness (Ra or the standard deviation, RMS); 2) the highest elements of roughness has the biggest influence therefore, it is necessary to take the ratio PV. However, a simple attempt to understand which of the parameters affects the most has not been successful: the graphs of Re_{1ef_Ra} and Re_{1ef_PV} turned out to be identical.

Table 2

Θ	s, mm
30	1.1
45	1.6
60	2.1
90	3.1
2.5 mm	5.6
5.5 mm	8.6

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As can be seen from Fig. 5 and Table 1 the scatter of Re_{1ef_Ra} and Re_{1ef_PV} is quite large, despite the same technique of roughness manufacturing from the calibrated sand was applied. Nevertheless, all the graphs clearly show a tendency: with increasing roughness angle Re_{1ef} successively decreases to $\Theta = 90°$, and then slightly increases and remains practically constant. This result was unexpected. According to some works, the most critical location of the roughness is near the sound line. The influence of the surface roughness on the generation of perturbations in the boundary layer is usually characterized by the parameter $Re_{kk} = \rho_k U_k k/\mu_k$, where ρ_k, U_k, μ_k are the values of density, velocity and viscosity corresponding to the flow parameters at height k over the model surface. According to the calculations the parameter Re_{kk} gives the maximum value at an angle $\Theta \approx 45°$ (near the sonic line), i.e. at this angle Re_{1ef} should be minimal. However, the minimum unit Reynolds number, at which the transition occurs immediately after the roughness is attained at $\Theta = 90°$. Perhaps this is because the flow continues to accelerate at the angle $\Theta \approx 45°$ stabilizing the perturbations and at $\Theta \approx 90°$ there is no favorable pressure gradient. In addition, at $\Theta \approx 90°$ the flow is already supersonic and it is possible the perturbations are amplified on the shock wave arising behind the roughness.

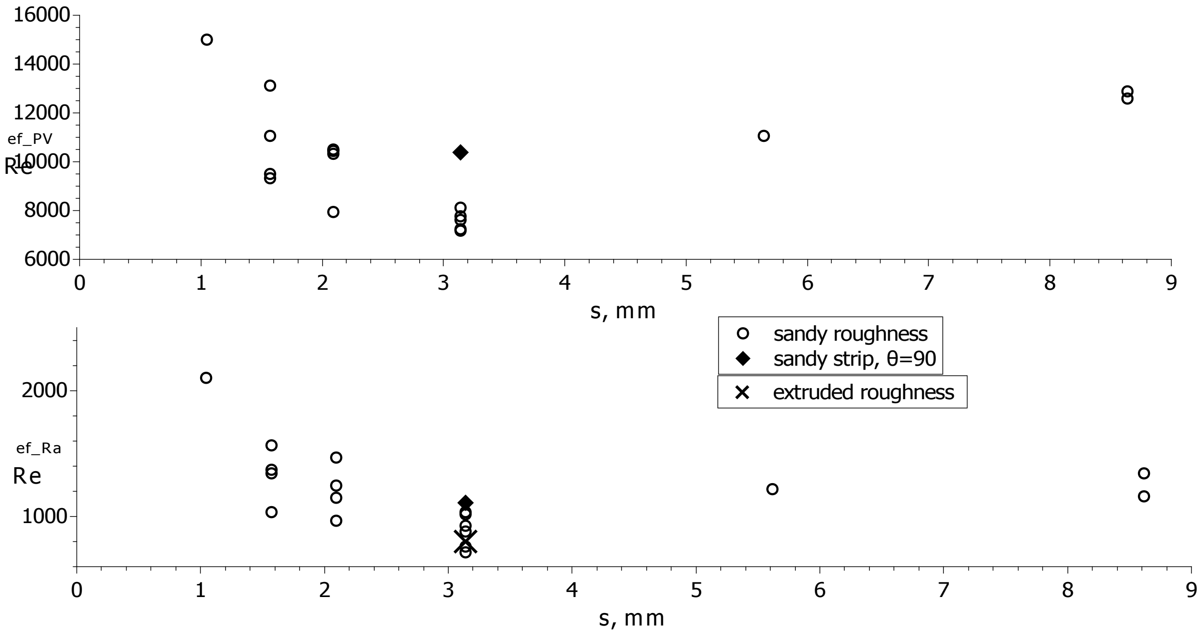

Figure 5: Dependence of the effective unit Reynolds numbers multiplied by Ra (bottom) and PV (above) from the area of roughness application

The graph Re_{1ef_Ra} (Fig. 5 below) also shows the value for the extruded roughness. Despite the fact that this roughness differs significantly from sandy roughness (for example, it does not form a step of the midline of the surface), the value of Re_{1ef_Ra} completely coincided with the results of the sandy roughness.
In order to understand the importance of the presence of a roughness on the entire surface of the nose-tip (over the entire angle Θ) experiments were carried out with a roughness applied in the form of a strip at $\Theta = 90°$ (Fig. 2c). It is seen that Re_{1ef_Ra} coincides with data for complete coverage. That definitely means it is not necessary to cover the entire nose-tip with a roughness to achieve a transition on the nose (to achieve Re_{1ef}). It is enough to cover a small area (strip) of roughness of a certain size. In addition, based on this result, one can conclude that the main role in the transition is played by the roughness value close to the end of the roughness zone. However, Re_{1ef_PV} turned out to be bigger. That is, perhaps in the case of a narrow roughness zone the PV values play a larger role than for a completely rough nose. To clarify this question further researches are needed.

4. Conclusions

It is shown that the roughness has the greatest influence on the transition when applied to the angle $\Theta \approx 90°$. In this case, the common Re_{kk} criterion is not satisfied. It is shown that to achieve an effective Reynolds number, the presence of a roughness is not necessarily on the entire surface of the nose. A small area applied at a certain angle is enough to obtain a transition. This means the key role in the transition is played by the roughness, which is directly on the boundary of the rough-smooth wall.

This work was financially supported by the Russian Science Foundation (Grant No. 14-11-00490).

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