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INVESTIGATION OF BOUNDARY LAYER LAMINAR-TURBULENT TRANSITION ON A SURFACE OF DELTA WING IN HYPERSONIC FLOW

V. Brazhko*, G. Dudin, N. Kovaleva*, I. Lipatov*, A. Skuratov*, A. Vaganov***

**Central Aerohydrodynamic Institute (TsAGI)*
1, Zhukovsky st., Zhukovsky, Moscow region, 140180, Russia
Email: alexvaganov@yandex.ru
***Moscow Institute of Physics and Technology*
16, Gagarin st., Zhukovsky, Moscow region, 140180, Russia
Email: dudin@falt.ru

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Abstract. The purpose of this work is experimental investigation of the laminar-turbulent transition on the surface of delta wing at hypersonic flow. Transition was diagnosed on heat flux distribution. Reynolds numbers of transition onset and transition end have been determined in the dependence of an angle of attack. It's shown that in the region of turbulent wedges on the wing surface heat flux more than tree times exceeds heat flux in the laminar region. Laminar-turbulent transition happens earlier near the leading edge with smaller bluntness radius.

The reliable prediction of flowfields over hypersonic vehicles including skin friction and heat transfer information involves the determination of the location and extent of the region of laminar-turbulent transition.

The purpose of this work is investigation of aerodynamic heating and laminar-turbulent transitions on the surface of the delta-shaped wing with blunt leading edges. Diagnostics of boundary layer laminar-turbulent transition on the wing surface is made on heat flux distribution. Method of the thermal sensitive coatings was used for this purpose. Tests were carried out in TsAGI's T-117 wind tunnel at Mach number $M_\infty = 7.5$.

The model represents the delta wing with sweep of the leading edges $\chi = 75^0$ and length L=599 mm. The nose part of the wing has a spherical bluntness of R=6 mm radius. Leading edges of the wing have the cylindrical-shaped form with radius r = 3 mm at one edge and r = 6 mm at another. It's made with the purpose to determine a radius influence on the laminar-turbulent transition region allocation. The wing has been manufactured of the heat insulator material AG-4.

The method of thermal sensitive coatings has been widely applied for heat flux measurements[1]. With the help of this method it's easy to reveal all zones of strong and weak heat transfer on a model surface. It's especially important at three-dimensional flows escorting with the shock waves interference, formation of areas of boundary layer separation, and also presence of laminar-turbulent transition of boundary layer. Results of experiments are obtained in easily visual form. Therefore, usually experimental researches of aerodynamic heating of the models begin with application of this method. In the places of maximum heat fluxes on a model surface, thermal sensitive coating is melted first of all. The contrasting border of the melting (isotherm) moves over the model surfaces during the test. Its motion from the moment of the model input in freestream is fixed by several video cameras.

Tests were carried out in TsAGI's T-117 wind tunnel[2]. The contoured nozzle designed for M_∞=7.5 was used. The nozzle-exit diameter equals 1 m. The test section of T-117 wind tunnel represents Eiffel chamber above which the gear for fast input of the models into freestream is located. The model has been installed on this gear. Total pressure changed from P_t=10 bar up to 24 bar, stagnation temperature was $T_t = 750$K. It corresponds to change of the Reynolds number over the range $Re_{\infty,L} \approx (1.4 \div 4.0)\times10^6$. As the thermal sensitive coating with the melting temperature $t_{melt} = 40^0$C was used, the temperature factor was $\overline{T}_w = \frac{T_{melt}}{T_t} = 0.42$.

Video frames patterns of the thermal sensitive coating melting on the wing surface obtained at angle of attack $\alpha=5^0$ and Reynolds number $Re_{\infty,L} = 1.37\times10^6$ are shown in Figure 1. On these frames the edge with bluntness r=3 mm is located below, and with radius r=6 mm − above. Isocaloric lines q/q_s distribution on the wing surface is presented in Figure 2. Relative heat flux values q/q_s indicated near each frame are realized on the border of thermal sensitive coating melting. Here q_s is the heat flux value at the model forward stagnation point. This value was calculated by Fay-Riddell formula for R=6 mm. Inside melting zone value q/q_s is higher, and outside is lower, than on the border.

For present of the results, 3 longitudinal sections corresponding to Y=0, Y=±52 mm and 5 cross sections X=100, 200, 300, 400 and 500 mm have been chosen. X coordinate at the section Y=0 is counted from the nose bluntness, and at another longitudinal sections – from intersection of this section with the leading edge contour. Y-axis is directed to the leading edge with bluntness radius r=6 mm (see Figure 2). Value X_{max} is 599 mm at Y=0 and is X_{max}=421 mm at Y=±52 mm.

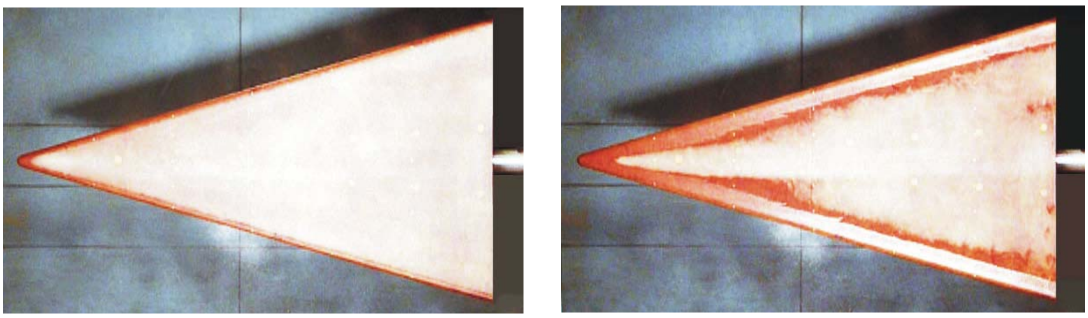

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Figure 1. Video frames with thermal sensitive coating. $Re_{\infty,L} = 1.37\times10^6$, $\alpha=5^0$. 1 – q/q_s=0.042, 2 − q/q_s=0.019

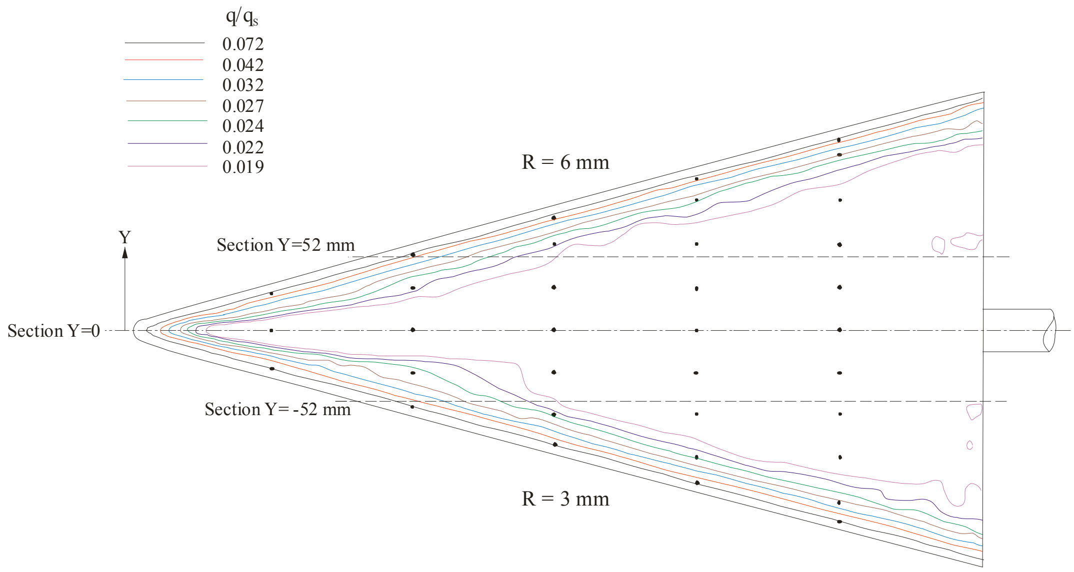

Figure 2. Isocaloric lines distribution. $Re_{\infty, L} = 1.37 \times 10^6$, $\alpha = 5^0$

On character of lines q/q_s=const distribution on the surface, we can conclude that completely laminar flow has been realized. Plots with relative heat flux distribution in longitudinal and cross sections for this flow regime are submitted in Figures 3 and 4. Relative heat flux distribution in longitudinal directions confirms laminar boundary layer state.

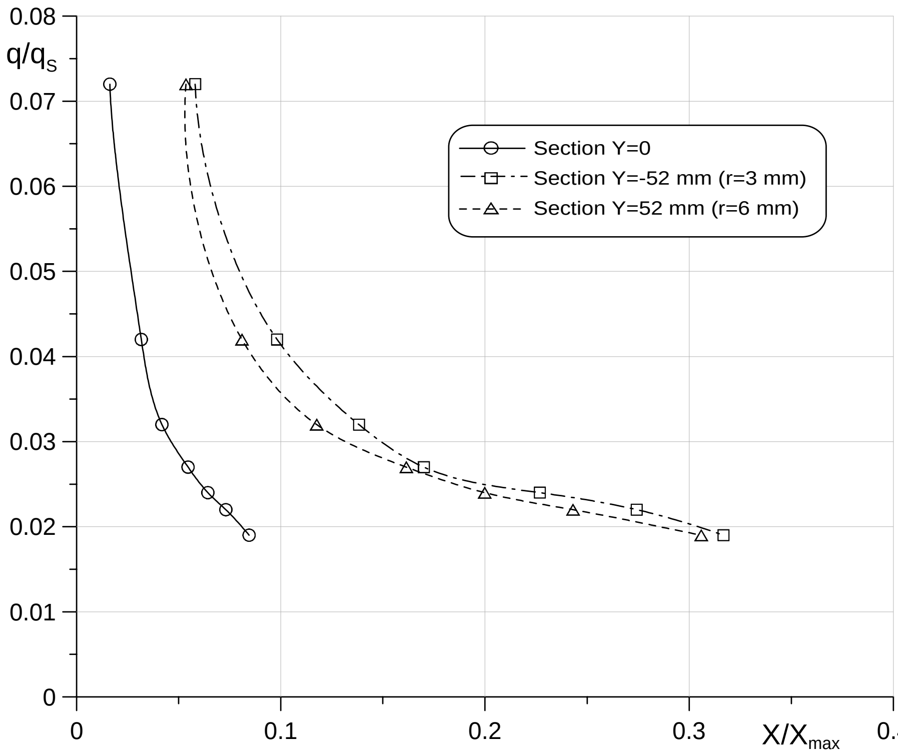

Figure 3. Relative heat flux distributions in longitudinal directions at Y=0 and Y=±52 mm. $Re_{\infty, L} = 1.37 \times 10^6$, $\alpha = 5^0$

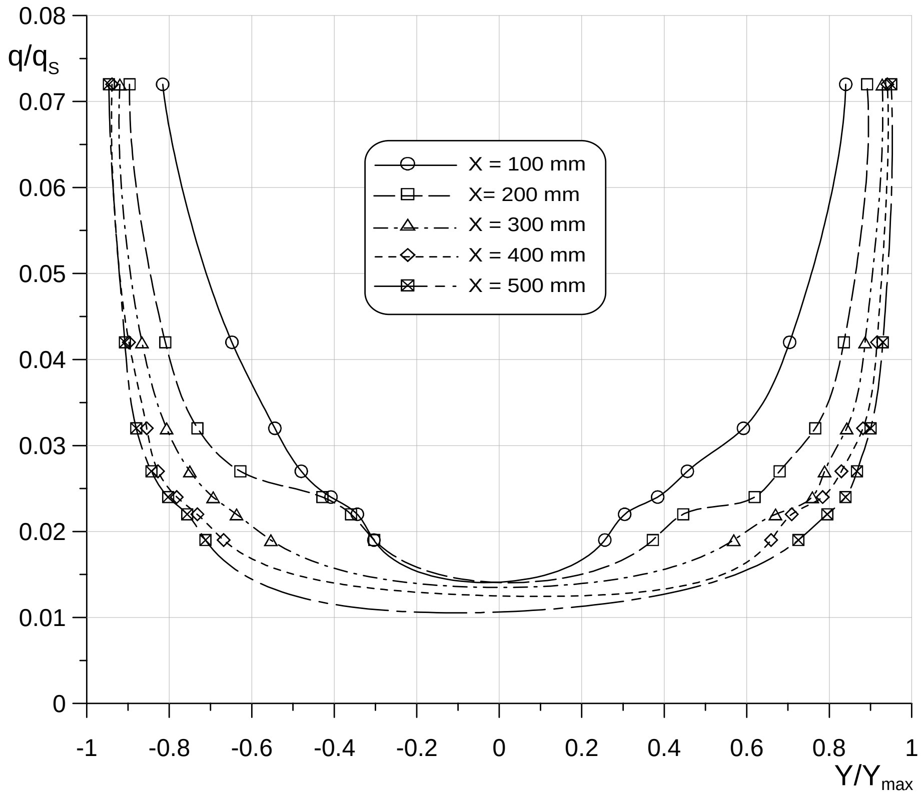

Figure 4. Relative heat flux distributions in cross directions. $Re_{\infty,L} = 1.37\times10^6$, $\alpha=5^0$

As far as Reynolds number increase, heat flux patterns on the wing surface are changed. Video frames patterns of the thermal sensitive coating melting on the wing surface obtained at zero angle of attack and Reynolds number $Re_{\infty,L} = 4.02\times10^6$ are shown in Figure 5. There are two wedge-shaped areas of thermal sensitive coating melting on the rear wind surface (further − turbulent wedges), heat flux values in which are close to the corresponding values in a vicinity of the leading edges. Formation of these areas is connected with a boundary layer laminar-turbulent transition on these wing surfaces. In the beginning, turbulent wedges exist separately, then at small relative heat flux values, they close among themselves at a vicinity of the wing symmetry plane. Appearance of the narrow band of thermal sensitive coating melting near the nose bluntness at the edge with r = 3 mm is connected with a vorticity generated by curvature break in the region of nose bluntness and leading edge coupling. Distribution of isocalorical lines on the wing surface is submitted in Figure 6.

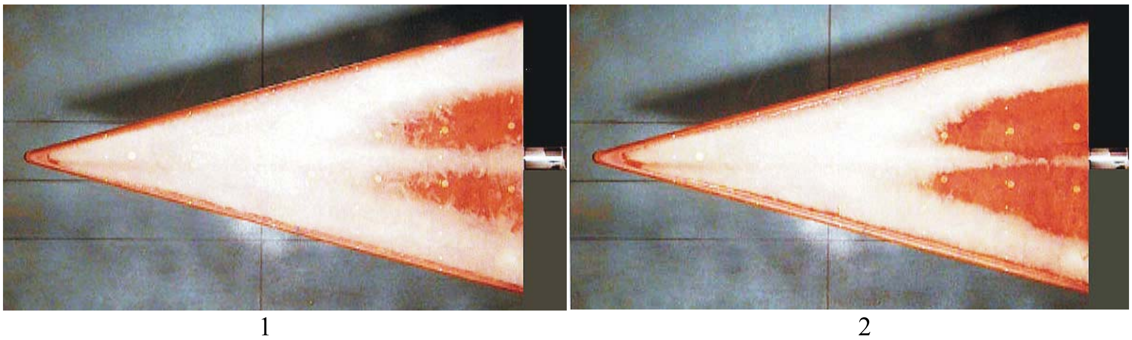

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Figure 5. Video frames with thermal sensitive coating. $Re_{\infty,L} = 4.02\times10^6$, $\alpha=0$. 1 – $q/q_s=0.022$, 2 − $q/q_s=0.018$

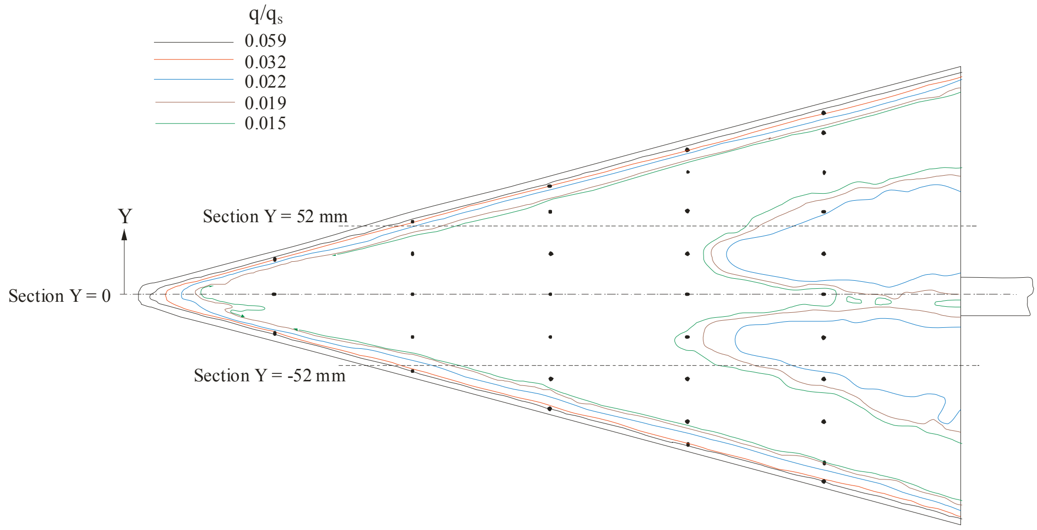

Figure 6. Isocaloric lines distribution. $Re_{\infty,L} = 4.02\times10^6$, α=0

From Figures 5 and 6 reviewing it's possible to draw the conclusion that on the wing side with radius r=3 mm boundary layer transition begins a little earlier than on the wing side with the leading edge r=6 mm. On maximum heat flux values at the end of transition region such change of edge radius does not influence in the limit of measurements accuracy.

Approximately the same heat transfer patterns are observed at other investigated angles of attack when Reynolds number is $Re_{\infty,L} = 4.02\times10^6$.

Summary graphs of relative heat flux distributions in the longitudinal sections Y = ±52 mm (see Figure 6) are presented in Figures 7 and 8 for all investigated model angles of attack. Besides, the approximate positions of the points of laminar-turbulent transition onset (arrows upwards) and end (arrows downwards) are indicated in these Figures. Increase of the angle of attack results in sharp grows of heat flux in the region of turbulent wedges. Moreover, points of transition onset and transition end move upstream at that. Thus, the $(q/q_s)_{max}$ value at the end of a transition range approximately in 3 times exceeds the corresponding laminar value in the point of transition onset.

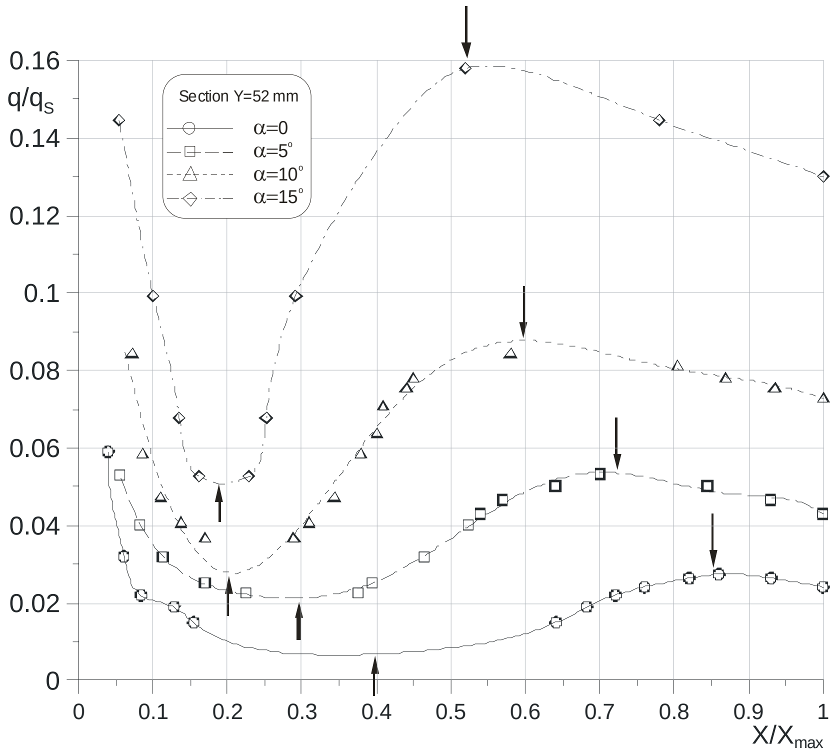

Figure 7. Relative heat flux distribution in longitudinal direction at Y=52 mm. $Re_{\infty, L} = 4.02\times10^6$

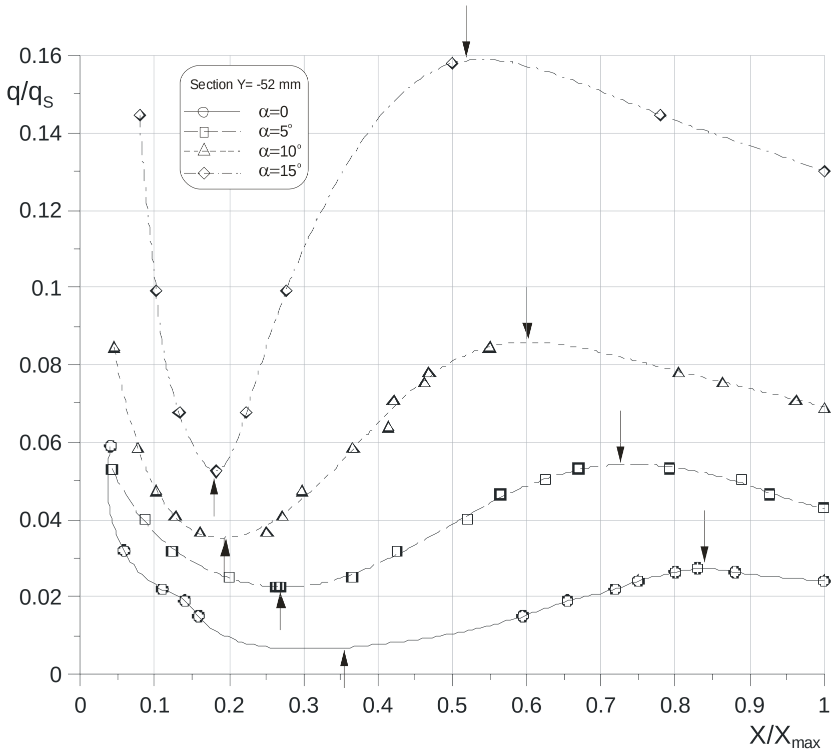

Figure 8. Relative heat flux distribution in longitudinal direction at Y=-52 mm. $Re_{\infty, L} = 4.02\times10^6$

Coordinates of the points of laminar-transition onset X_t and transition end X_T in the cross sections Y=±52 mm versus angle of attack are shown in Figure 9. Corresponding Reynolds numbers Re_t and Re_T are indicated in Figure 10. Re_t and Re_T numbers were calculated on freestream parameters and the distances from the leading edge X_t and X_T correspondingly.

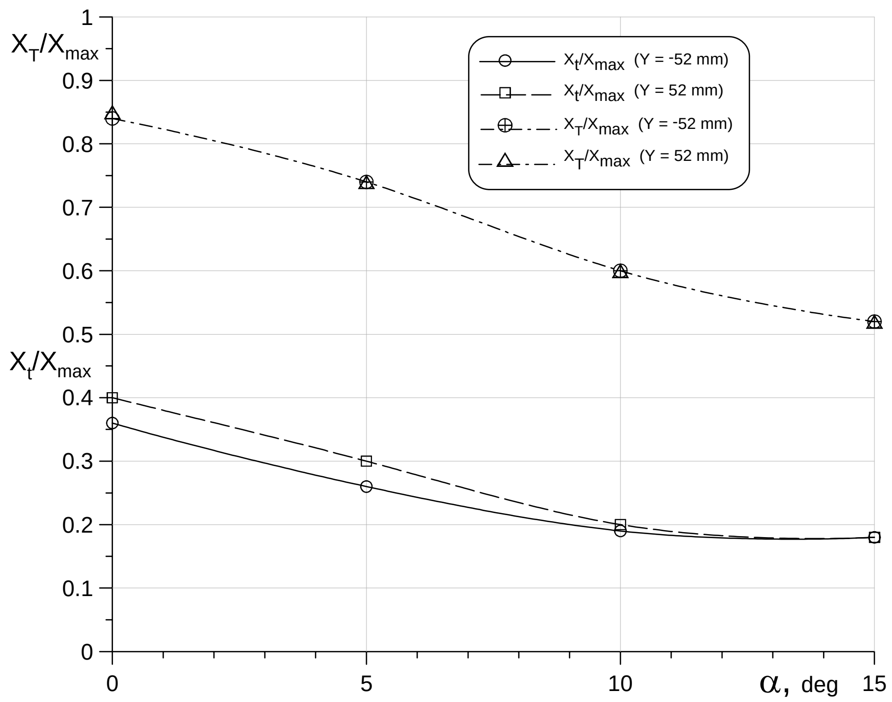

Figure 9. Coordinates of the points of transition onset X_t and transition end X_T. $Re_{\infty,L} = 4.02\times10^6$

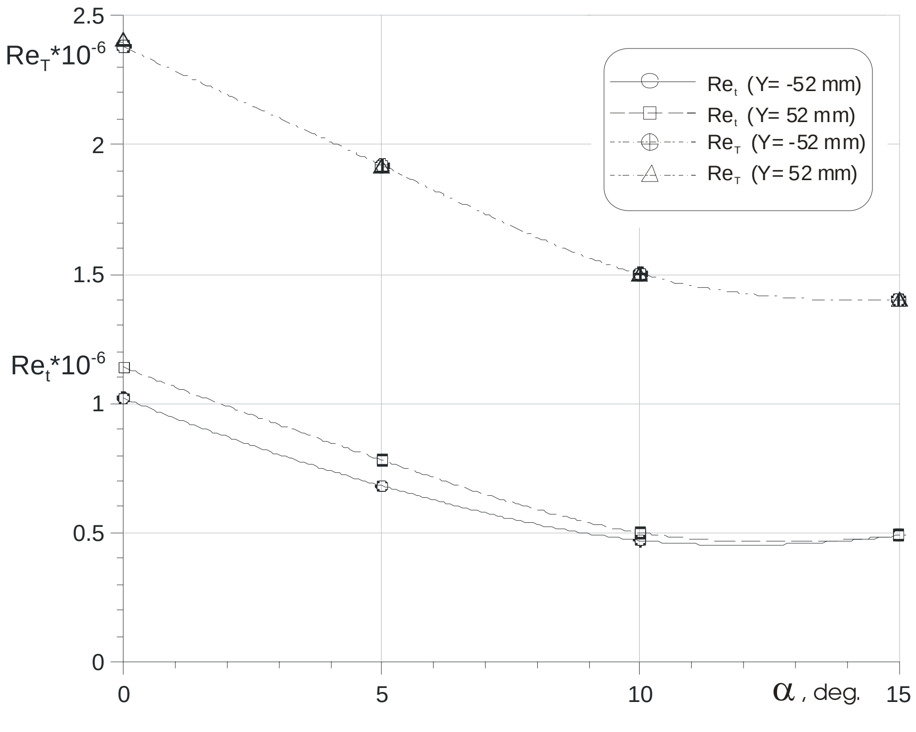

Figure 10. Reynolds numbers of transition onset Re_t and transition end Re_T. $Re_{\infty,L} = 4.02\times10^6$

The most strong angle of attack influence on X_t/X_{max} decrease in the region of laminar-turbulent transition takes place at angle of attack range $\alpha=0\div10^0$ (from X_t/X_{max}=0.4 to 0.2). At further angle of attack growth up to 15^0, the distance to the point of transition onset decreases up to X_t/X_{max}=0.18. Similar character has dependence of Reynolds numbers Re_t and Re_T of angle of attack. Minimal Re_t value has been reached at angle of attack $\alpha=10^0$ and it equals 0.5×10^6. The minimum distance up to the point of the transition end is realized at $\alpha=15^0$ ($X_T/X_{max}\approx0.52$), the corresponding Reynolds number is $Re_T \approx 1.4\times10^6$.

CONCLUSION

Investigations of heat transfer on the delta-wing surface at M_∞=7.5 have shown:

● At Reynolds number $Re_{\infty,\ L} \approx 1.4\times10^6$ laminar boundary layer exists on the whole wing surface.

● At Reynolds number $Re_{\infty,\ L} \approx 4\times10^6$ heat flux distribution on the wing surface is essentially nonmonotonous. It is connected with boundary layer laminar-turbulent transition. Two zones of intensive heat transfer (turbulent wedges) appear near the both leading edges. These zones exist at all investigated angles of attack (α=0÷15^0).

● Angle of attack increase leads to growth of heat flux in the turbulent wedges and displaces upstream the points of onset and end of laminar-turbulent transition. Heat flux values at the point of turbulent transition end are three times greater than corresponding value at the point of transition onset.

● Most strong angle of attack increase on X_t distance decrease takes place at the angle of attack range α=0÷10^0 (approximately from X_t/X_{max}=0.4 to 0.2). Similar character has behavior of transition onset Reynolds number Re_t. Minimal value Re_t number reaches at angle of attack α=10^0 and it equals 0.5×10^6.

● On the wing side with leading edge radius r=3 mm boundary layer transition begins a little earlier than on the wing side with the leading edge radius r=6 mm.

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