EXPERIMENTAL INVESTIGATION AT MACH NUMBER M = 7.5 OF AERODYNAMIC HEATING AND LAMINAR-TURBULENT TRANSITION ON BLUNT DELTA WING

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Delta shaped wings are often used for high-speed flight. In accordance to it, an investigation of heat transfer and laminar-turbulent boundary layer transition on delta wing surfaces is very interesting. At a region of turbulent boundary layer existence, the heat fluxes values increase twice or more times in comparison to their laminar level. Behind transition regions a reconstruction of reattachment flow in front of deflected control surfaces, for example, flaps, takes place. It leads, in one's turn, to changing both heat and aerodynamic streamlined body characteristics. A number of activities [1 - 6] devoted to investigation of such transition on delta wings surface with sharp leading edges. In some papers (see, for example, [7, 8]) it was researched an influence of leading edges bluntness radius on a transition at leeward delta wing surface. It shown that laminar-turbulent boundary layer transition on delta wing depends on many parameters such as freestream Mach number, unit Reynolds number, angle of attack, sweep angle, wing leading edges bluntness radius and others. However, using of these results and some other activities data is not sufficient for understanding of rules determined the existence and location of boundary layer transition regions on wing surface.

In present activity there are given experimental results obtained at Mach number M=7.5 and angles of attack $\alpha = 0 - 15^\circ$ on delta wing leeward surface with flaps that can be deflecting. An apex and one of wing leading edges had a 6 mm bluntness radius; the bluntness radius of another edge was 3 mm. A sweep angle of wing leading edges was $\chi = 75^\circ$.

Experimental investigations carried out at TsAGI wind tunnel T-117 [9].

The main parameters, which realized during these experiments performing, presented in a Table.

<table>
<thead>
<tr>
<th>№</th>
<th>$\alpha$ [°]</th>
<th>$\delta_1$ [°]</th>
<th>$\delta_2$ [°]</th>
<th>$M_\infty$</th>
<th>$P_t$ [kr/cm$^2$]</th>
<th>$T_t$ [K]</th>
<th>$Re_1*10^{-6}$ [1/M]</th>
<th>$Re_L*10^{-6}$</th>
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<td>1</td>
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<td>0</td>
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<td>6.72</td>
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<td>25.35</td>
<td>745</td>
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<td>3.84</td>
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Here:

$\alpha$ - a model angle of attack,
$\delta_1$ and $\delta_2$ – the angles of right and left flap deflection,
$M_\infty$ – freestream Mach number,
$P_t$ and $T_t$ – stagnation pressure and temperature,
$Re_1$ – unit Reynolds number calculated by freestream parameters,
$Re_L$ – Reynolds number calculated by freestream parameters and by wing length $L = 599$ mm.

In Fig. 1 presented a model scheme utilized at the experiments. At the scheme there are pointed
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the coordinates of sections chosen for tests outcomes presentation. A model is designed of delta wing shape with leading edges sweep angle $\chi = 75^\circ$, apical spherical bluntness ($R = 6$ mm) and edges cylindrical bluntness ($r = 3$ and 6 mm). It made with a purpose of defining of possible $r$-value influence on location of laminar-turbulent boundary layer transition regions. At model tail part there are located two flaps that can have the deflection angles of $\delta = 0$, $10^\circ$ и $20^\circ$ with respect to wing lower surface.

![Figure 1](image.png)

For measuring of heat flux directed to wing surface during these tests it was used a thermal sensitive coatings technique [11]. In connection to it, a wing was made of small heat transfer material. At places of maximal heat flux value a thermal sensitive coating of white color on a model surface melts in a first turn and becomes transparent. Contrasting melting border (isotherm) moves along a model surface during an experiment. This motion fixed by some video cameras from model bringing into a stream.

On bodies with nose spherical bluntness a measured heat flux $q$ usually refers to heat flux value $q_s$ calculated at stagnation point of nose bluntness using Fay-Riddell formula [10] for freestream parameters at given test run starting. Experimental results presented as a number of isolines $q/q_s$ on a model surface and as a number of plots of $q/q_s$ distribution at given sections. A stagnation free stream temperature $T_t$ used as a characteristic one during $q$ value calculation.

In Figure 2 there is shown a picture of a thermal sensitive coatings melting on a lower wing surface (a frame from a video-file) obtained at angle of attack $\alpha = 5^\circ$ and at the Reynolds number $Re_L = 3.68 \times 10^6$. Flaps deflection angles $\delta_1$ and $\delta_2$ equals zero.
The $q/q_s=0.036$ value in this Figure corresponds to a thermal sensitive coatings melting border. Inside melting zone $q/q_s$ values are larger in comparison to border values. However, outside such zone the above-mentioned values are less. It is visible, that in a wing back part there are arisen two big wedge-shaped areas of thermal sensitive melting (further – turbulent wedges). The heat flux values at these regions are close to that ones at the neighborhood of leading edges. These areas generation connected to a laminar-turbulent transition of a boundary layer at these parts of wing surface. It is obvious also that a changing of leading edges bluntness radius value in such limits influences only a little on transition field onset and its sizes.

The $q/q_s=\text{const}$ isolines distribution on wing/flaps lower surface for this overflow mode is presented in Figure 3.

From this picture it follows that a boundary layer transition inside turbulent wedges finishes still up to wing trailing edge (lines $q/q_s=0.06$) and a turbulent boundary layer exists on the most part of flaps surface.

A wing angle of attack increasing up to $\alpha = 15^\circ$ (Figure 4) leads to appearance of another boundary layer transition region in its central part. This phenomenon is caused by disturbances come from wing apex.
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Figure 4. $M=7.5$, $\alpha = 15^\circ$, $Re_L = 3.84 \times 10^6$, $\delta_1 = \delta_2 = 0$

In other words at this model overflow mode on the most part of wing lower surface the stream has a transitional or turbulent character.

![Figure 4](image)

It testifies by plot presented in Fig. 5. At the end of transition zone heat fluxes values both on angle of attack plane ($Y=0$) and on lateral sections passed through turbulent wedges ($Y=\pm 52$ mm, see Figs. 2, 3) come to the same turbulent level.

In Figure 6 it is shown a distribution plot of relative heat fluxes values $q/q_s$ at $Y=-52$ mm sections in dependence on wing angle of attack. During $\alpha$ increasing, the points of onset and the end of laminar boundary layer transition into a turbulent one displace forward and heat fluxes in the end of transition region grow sharp. At the same time, a gradient of heat flux intensification in a transitional region increases and a transition zone length becomes less. At $\alpha = 5^\circ$ and for Reynolds number $Re_L \approx 1.3 \times 10^6$ a transition on a wing surface doesn’t take place and at a given section in Fig. 6 it is observed a merely laminar heat fluxes distribution.

![Figure 5](image)

![Figure 6](image)
As it seen from this picture a heat flux value relation \((q/q_s)_{\text{max}} \approx 0.06\) at an end of transition field at \(\alpha = 5^\circ\) and for number of \(Re_L \approx 3.68 \times 10^6\) exceeds the appropriate laminar relation more than 3 times. At the same time a maximal calculated relative value of heat flux on a wing edge with a bluntness radius of \(r=3\) mm equals \(q_{s\text{ edge}}/q_s = 0.197\). At an angle of attack \(\alpha = 15^\circ\) at the end of transition field a \((q/q_s)_{\text{max}} \approx 0.16\) and a calculated heat flux on this wing edge is \(q_{s\text{ edge}}/q_s = 0.279\).
In Figure 7a there is shown a picture of a thermal sensitive melting on a wing lower surface obtained at angle of attack $\alpha = 5^\circ$ and for Reynolds number $Re_L = 1.28 \times 10^6$. A flap deflection angle $\delta_1$ equals $20^\circ$ near a wing edge with bluntness radius $r=3$ mm and $\delta_2=10^\circ$ for a flap at a wing edge with $r=6$ mm. In Fig. 7b it is presented a frame from video recording of test run starting obtained at $Re_L = 3.56 \times 10^6$. In both pictures a value of $q/q_s=0.039$ corresponds to a border of thermal sensitive melting on a wing surface and a $q/q_s=0.086$ relation corresponds to the same border on a flap surface.

In Figures 8a, b there are presented the plots of heat flux relations distribution obtained for $\alpha = 5^\circ$ at a section of $Y= \pm 109$ mm passed through a flap middle (see Figure 3) for a case of undeflected flaps $\delta_1=\delta_2=0$ and for a case of flap deflection down on an angle of $10^\circ$ and $20^\circ$ as shown in Fig. 7.
At small Reynolds numbers in front of flap deflected on an angle of 20° it is observed a laminar boundary layer separation with sharp peak of heat fluxes at reattachment point ($X/X_{\text{max}} \approx 1.17$) on a flap. A $(q/q_s)_{\text{max}} \approx 0.43$ relation at reattachment point exceeds in 3 times a calculated value of heat flux $q_{s\text{ edge}}/q_s = 0.139$ on a wing leading edge with bluntness radius of $r=6$ mm.

At a number of $Re_L = 3.56 \times 10^6$ in a field of turbulent wedge existing on a wing surface a boundary layer separation in front of flap deflected on an angle of $\delta = 20^\circ$ doesn’t take place. In both plots a vertical line on an $X/X_{\text{max}}$ axis at the right side designates a flap trailing edge.

In Figure 9 there are shown some $q/q_s$ value distributions on a wing lower surface at cross-section located at a distance of $X=500$ mm from it apex.
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At $\alpha = 5^\circ$ and for small $Re_{l}$ numbers, as was mentioned above, at the section a laminar boundary layer exists. At large Reynolds numbers you can see the formation of transitional and turbulent fields that at $\alpha = 15^\circ$ spread from $Y/Y_{\text{max}} \approx -0.88$ to $Y/Y_{\text{max}} \approx 0.85$. An $Y_{\text{max}}$ coordinate corresponds to an intersection point of cross-section and wing leading edges generatrixes (see Figure 1).

In Figure 10 it is shown a plot of Reynolds numbers dependence of the transition onset $Re_{t}$ and its end $Re_{T}$ defined at cross-sections $Y = \pm 52$ mm on angle of attack $\alpha$. The numbers of $Re_{t}$ and $Re_{T}$ calculated by free stream parameters and by distances to points $X_{t}$ and $V_{T}$ of transition onset and its end correspondingly.

![Figure 10](image-url)

The most effective influence of angle of attack increasing on Reynolds number diminishing corresponding to transition onset occurs at a range of $\alpha = 0 - 10^\circ$ (approximately from $Re_{t} \approx 1.1 \times 10^{6}$ to $Re_{t} \approx 0.5 \times 10^{6}$). During $\alpha$ increasing further still up to $\alpha = 15^\circ$ a Reynolds number value does not change practically. Reynolds number minimal value of transition end is realized at $\alpha = 15^\circ$ and equals $Re_{T} \approx 1.4 \times 10^{6}$. Here there are also marked the corresponding data obtained at an activity [6] under a Mach number $M=8$ on a wing with sharp leading edges. At zero angle of attack, a transition onset Reynolds number for such wing is approximately two times greater than for a wing with blunted edges. During $\alpha$ increasing, the $Re_{t}$ values measured at both papers draw together. A transition field length from an activity [6] is less than for a wing with blunted edges. Apparently, these divergences caused by difference in freestream parameters, edge geometry and measuring sections location.

As it seen from Figs. 2 - 4, an external border of turbulent wedge is practically parallel to wing leading edge. Then, if a measuring section is located farther from an angle of attack plane than a turbulent wedge apex is, that this fact does not influence sufficiently on $X_{t}$ and $Re_{t}$ values. These values can grow considerably in that case if a given section is located at another side of turbulent wedge apex. Because of that before model, preparing by sensors it should perform a visualization of heat transfer features position on its surface, for example, with an aid of thermal sensitive coatings.
Conclusions

An investigation of aerodynamic heating of delta wing model with flaps was carried out at wind tunnel T-117 under Mach number $M = 7.5$ using thermal sensitive coatings technique. The aim of such researches was both obtaining the results about heat flux data on model surface and fields position defining of laminar boundary layer transition into a turbulent one.

The presented results demonstrated that for $\alpha = 5^\circ$ and for small Reynolds numbers $Re_L = (1.37 \text{ and } 1.28) \times 10^6$ an almost completely laminar flow is realized on a wing lower surface. But in this case three-dimensional fields of boundary layer separation take place in front of two flaps deflected on angles of $\delta_1 = 20^\circ$ and $\delta_2 = 10^\circ$ correspondingly. On flap with deflection angle of $20^\circ$ it observed a local peak of heat fluxes that is typical for boundary layer reattachment regions. A maximal heat flux value at this peak is approximately 20 times greater than heat flux value on a wing before separation line.

At $Re_L = (3.54 - 4.02) \times 10^6$ numbers heat fluxes distribution on a model lower surface has a sufficiently non-uniform character. On a windward surface, it connected to generation of two local fields of laminar-turbulent transition (turbulent wedges) near an each leading edge at the whole range of model angle of attack $\alpha$ under consideration. These turbulent wedges caused by transition near wing leading edges exist for all $\alpha$ values. An angle of attack increasing leads to sharp rising of heat fluxes values inside a turbulent wedges field. At the same time it observed a displacement forward of transition onset and its ends. Heat relations $(q/q_s)_\text{max}$ at the end of transition field exceed approximately in 3 times the same values for laminar flow at a point of transition onset.

At $\alpha = 5^\circ$ the turbulent wedges occupy the most part of the wing surface in front of deflected flaps. One could say that boundary layer separation in front of flaps at the regions of transitional and turbulent streams does not take place. This conclusion follows from the fact that in turbulent wedges before a wing trailing edge the regions of small heat fluxes values not observed. Maximal heat flux values on a flap with deflection angle of $10^\circ$ are approximately 4 times greater than on undeflected flap. At deflection angle of $\delta_1 = 20^\circ$ these values are almost 10 times greater.

The most intensive influence of angle of attack growth on $Re_T$ number diminishing at sections of $Y = \pm 52$ mm occurs at a range of $\alpha = 0 - 10^\circ$ (approximately from $Re_T \approx 1.1 \times 10^6$ to $Re_T \approx 0.5 \times 10^6$). During $\alpha$ increasing further still up to $\alpha = 15^\circ$ a Reynolds number value does not change practically. Minimal transition end Reynolds number value is realized at $\alpha = 15^\circ$ and equals approximately $Re_T \approx 1.4 \times 10^6$.

In a case of $\alpha = 10^\circ$ on a wing lower surface in it central part near a trailing edge it is observed an additional region of laminar-turbulent transition caused by nose bluntness disturbances. At $\alpha = 15^\circ$ this region develops into strongly pronounced turbulent wedge. In this wedge, a boundary layer transition end is located in a point with coordinate $X_T/X_{\text{max}} \approx 0.6$.

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REFERENCES


