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Free Stream Turbulence Effect on the Flow Structure over the Finite Span Straight Wing

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***Abstract*:** Flow visualization tests have been performed to examine the structure of the near-wall flow over a low-aspect ratio straight wing installed at various angles of attack α and chord Reynolds number $Re_c = U_\infty c/\nu = 1.76 \times 10^5$. The experiments were carried out at two free-stream turbulence levels, $\varepsilon = 0.1\%$ and $\varepsilon = 1\%$, the latter one having been achieved using a baffling grid. To visualize the flow, termochromic cholesteric liquid crystals and digital processing of video images were used. At the low turbulence level and $\alpha = 27^\circ$, a flow stall on the lee side of the wing was observed, with a pair of large-scale vortices rotating in the wing plane. Simultaneously, no vortex structures were observed on the windward wing surface. It was found the flow patterns on either side of the wing significantly changed with increasing free-stream turbulence level. A separation bubble appeared near the leading edge on the lee side of the airfoil at $\varepsilon = 1\%$, and large-scale stationary longitudinal vortices originated over the wing windward surface. The number and sizes of the longitudinal structures were found to be dependent on the angle of attack.

***Keywords*:** straight wing, boundary layer, longitudinal vortices, liquid crystals.

1. Introduction

The flow modeling around wings and turbine blades includes a wide spectrum of problems still remain unresolved. In particular, generation and evolution of boundary layer structure has not been completely studied in spite of the wing aerodynamics well explored in the past. The need in such investigations is due to the fact that boundary layer structure strongly affects on drag and lift (and, hence, performance and costs) of specific aircraft design. Owing to high sensitivity of boundary layer to initial and wall conditions there is a strong necessity in obtaining reliable experimental data concerning the problem.

The flows with separation have been studied most thoroughly for the lee side of the wing. As far as our knowledge goes, no panoramic visualization data were obtained for the flow on the windward wing side, and no vortex structures were reported. The latter may be attributed to insufficient sensitivity of traditional methods of flow visualization. At the same time, it is known, the methods of visualization by tufts, oil film, china clay, naphthalene sublimation, may themselves disturb flow masking real flow pattern. Therefore, it seems, that using liquid crystals encapsulated in thin polymer films provides complementary reliable panoramic data on fine boundary layer structure. Previously, visualization methods based on using liquid crystals have been successfully used to study separation flows on a finite-span straight wing in a wide range of angles of attack and low subsonic Reynolds numbers (Dovgal et al., 1995; Zharkova et al., 1998a; Zharkova et al., 2000).

The work was aimed at revealing the fine structure of a boundary layer over the wing by liquid crystal coatings in a wide range of angles of attack. The second purpose of the experiment was to visualize the effect of free stream turbulence on the flow structure on the both wing sides.

At present the effect of high free stream turbulence on the boundary layer flow was studied in detail to flat plate only (Alfredsson and Matsubara,1996; Kosorygin and Polyakov, 1990; Bakchinov et al., 1998). But experimental data about flow structure in the areas of big negative pressure gradient are not sufficient. It was supposed that disturbances coming into the boundary layer from the free stream are attenuated and the flow is unseparated and laminar. However, the results obtained by LC thermography in the work show that appearance of the vortex structures is possible in this case.

2. Experimental Setup and Conditions

The experiments were carried out in the low-turbulence subsonic wind tunnel MT-324 of the Institute of Theoretical and Applied Mechanics at a chord Reynolds number $Re_c = 1.76 \times 10^5$. The dimensions of the open test section were 200 mm × 200 mm × 750 mm. The level of free stream turbulence $\varepsilon = u'_{rms}/U_\infty$ was 0.1%, where u'_{rms} is the root-mean-square value of the longitudinal component of velocity fluctuations and U_∞ is the free-stream velocity.

A model of straight wing (chord c = 228 mm, aspect ratio λ = 0.87, maximum relative thickness 16% at the distance 34% chord from the blunt leading edge) was used. The model, made of wood, had a symmetric airfoil and no concave surface parts. Its surface was covered by a thin stainless-steel foil that served as an electric heater. The scheme of the experiment is shown in Fig. 1.

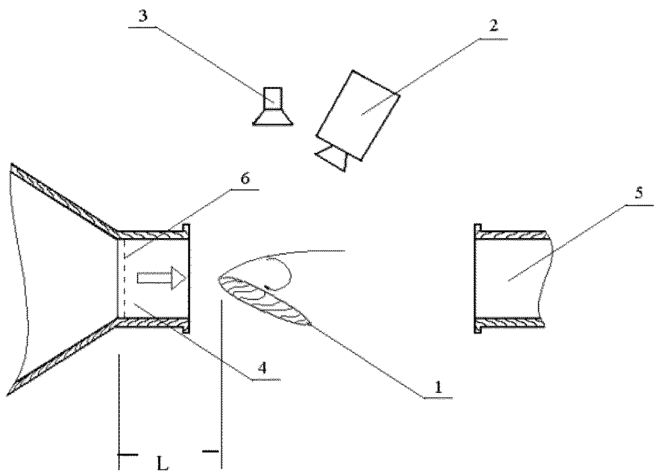

Fig. 1. Scheme of the experiment: 1 - model, 2 - camera, 3 - light source, 4 - confuser, 5 - diffuser, 6 - fine-mesh grid.

The experiments were carried out for two free-stream turbulence levels, 0.1 and 1%. The increased level of the free-stream turbulence in the test section was produced by a fine-mesh wire grid installed in the nozzle. The grid was made of a 0.3 mm-diameter wire, and its mesh size was 2.3 mm.

To gain information about the free-stream turbulence characteristics in the presence of the grid, hot-wire measurements of streamwise velocity fluctuations were made. These measurements were performed in the test section of the wind tunnel with and without model mounted inside. A comparison of results obtained has shown that, with the model in the wind-tunnel test section, the turbulence anisotropy increases. The turbulence decrement in the empty working part was found to well agree with the results of previous studies of grid-generated turbulence (Baines and Petersen, 1951). The turbulence level ε was about 1% near the leading edge of the model installed at a distance of 146 mesh sizes from the grid. The integral turbulence length scale Λ_u was determined by extrapolating the energy spectrum $E(f)$ to zero frequency. The integral time scale then obtained as $E(0)$ normalized with u'^2_{rms}. In this way, Λ_u was estimated to be within 3-4 mm at a distance of 10 mesh sizes upstream of the leading edge and 5-7 mm near it.

The flow in the boundary layer was visualized using polymer-encapsulated thermochromic liquid crystals. A thin (~25 microns) liquid-crystal film was expected not to disturb the flow pattern, nor to exert a noticeable influence upon the heat flux from the model.

The liquid-crystal thermography technique (Zharkova et al., 1998b) was used to obtain the mean temperature distribution on the wing surface. The interpretation of visualization data for stationary experimental conditions and boundary conditions under constant heat-flux density q at the wall, was based on the following. The surface parts colored in blue-violet indicated an increased temperature and, hence, a low local heat transfer. Whereas the parts colored in red indicated a relatively low temperature and an enhanced heat transfer. This interpretation was based on the expression $h = q/(T_{lc}-T_{ref})$ for the heat-transfer coefficient h, valid for the experimental conditions adopted (q = const), where T_{lc} is the wall temperature, and T_{ref} is the free stream temperature.

The colored images of the model surface were recorded by an image processing system. The temperature distribution was reconstructed using a calibration temperature T versus hue H, where H is one of the coordinates in the calorimetric system HSI (Hue, Saturation, Intensity). In the present study, all temperature maps were drawn without correction on the angular dependence of the selective reflection, since the optical arrangement has been chosen such that the difference between the incidence and reflection angles for the whole surface under study be no less than 15 degrees. Both the camera and the light source were installed under an angle close to the normal to the surface (except for a small area near the leading edge of the model). Therefore, the angular dependence of the LC selective reflection could not be considered.

3. Results and Discussion

The temperature distribution on the model, associated with the flow field near the wing, was visualized on its lee and windward sides by Liquid Crystal Thermography technique.

3.1 Effect of High Turbulence Level on the Lee Side Flow Structure

Figure 2 shows the temperature distributions on the model surface at ε = 1% for various angles of attack. Due to the longitudinal symmetry, only half of the wing surface is shown.

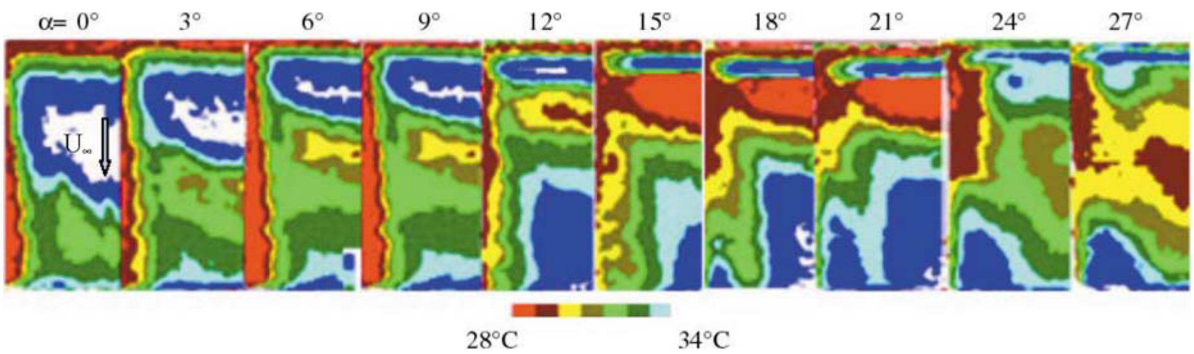

Fig. 2. Temperature maps for the lee side of the wing at ε = 1% and various angles of attack (half of the image).

The influence of high free stream turbulence on the flow structure has been studied most thoroughly for poststall conditions, when a flow separation from the leading edge of the wing emerged at angles of attack $\alpha \geq 24^\circ$.

The time series of frames (1- 4) shown in Fig. 3 for ε = 0.1% and 1% were captured at $\alpha = 27^\circ$ during a 10-s time interval as the temperature at the model surface was passing through the range of selective reflection of the LC coating.

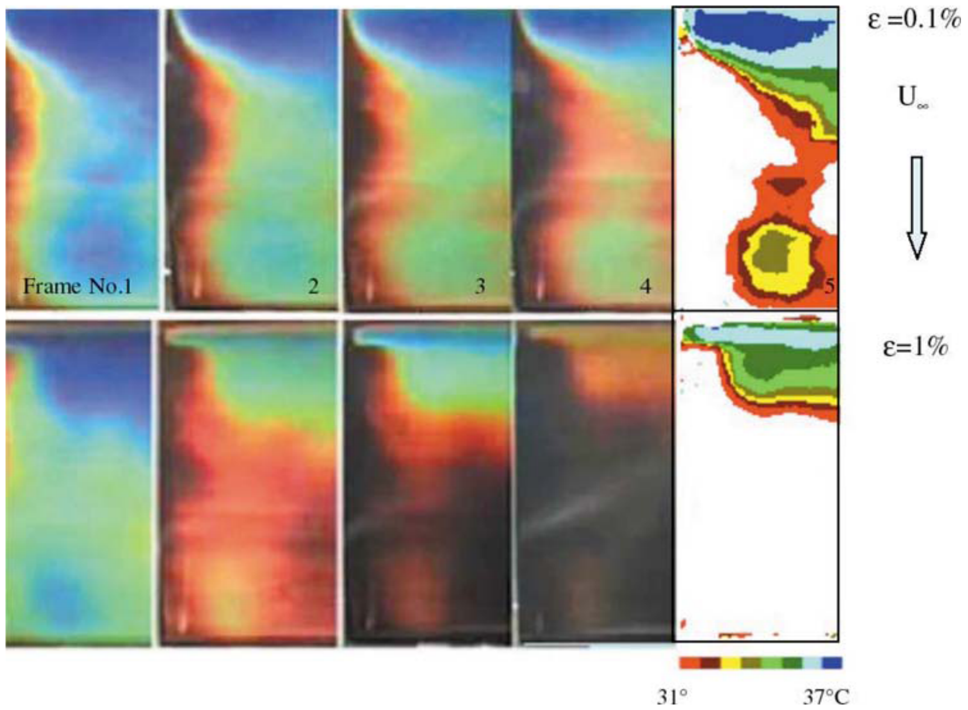

Fig. 3. Liquid-crystal visualization on the lee side at α = 27˚: 1~4 - movies for ε = 0.1% (upper row) and ε = 1% (lower row), half of the wing surface image. 5 - temperature map for the frame No.4.

Figures 2 and 3 are indicative of a strong non-uniformity of the temperature field featuring the flow structure in the boundary layer. To identify characteristic structures of the flow, additional oil-film (Fig. 4) and silk-thread visualization tests were carried out. A comparative study of the temperature fields and limiting-streamline visualization data obtained has allowed us to deduce the flow structure and elucidate the effect due to increased free-stream turbulence.

In both cases (ε = 0.1 and 1%), at α = 27˚ a leading-edge stall was observed. Over the wing, there was a reverse-flow region 1 (Fig. 4) between the tip vortices 2 formed by the stream overflow from the windward wing side to the lee one. In this region, two vortices, rotating in the wing plane, with foci 3 near the leading edge, were observed. An increase in the free-stream turbulence was found to substantially reduce the sizes of the foci of vortices 3 and cause in their displacement toward the leading corners. Near the leading edge of the wing, a narrow spanwise strip 4 emerged as wide as the whole wing span. The temperature inside this strip was higher than in other areal parts of the surface, pointing to a low rate of heat transfer there. This strip seems to be a stagnation region of the separation-bubble type. Downstream this zone, the temperature is maximal at the foci of vortices 3. The surface is cooled most rapidly in the central part of the wing, where the reverse flow region comes to the end. In the trailing part of the model the temperature is increased again due to the tip vortex effects 5.

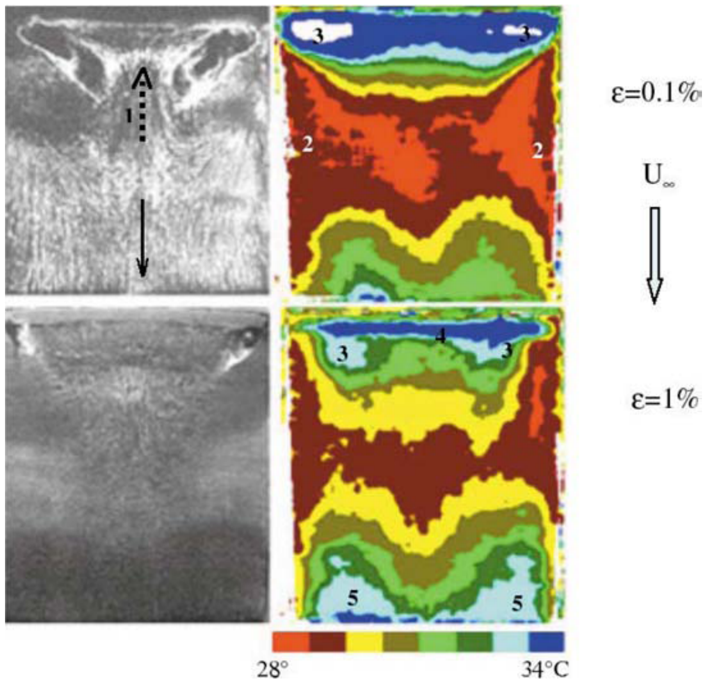

Fig. 4. Oil-film visualization (left images) and temperature maps (right images) at α = 27°and two ε: 1 - reverse flow region, 2 - zone of the tip vortices, 3 - foci of the leading edge vortices, 4 - stagnation region, 5 - zone of the tip vortices effects.

3.2 Effect of High Turbulence Level on the Windward Side Flow Structure

The typical results of the investigation are shown in Figs. 5-8. It was stated that the flow patterns over the windward side of the wing in the presence of grid and without one differed drastically from each other.

The time series of flow pattern without grid at low level of turbulence is shown in Fig. 5. As it is seen in this case, gradual wall temperature increase downstream from flow attachment line is observed. That is due to boundary layer thickening. No longitudinal structures were observed in the flow.

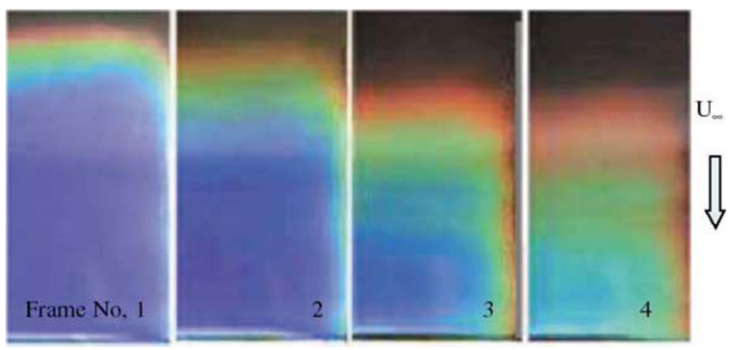

Fig. 5. Liquid-crystal visualization on the windward side at ε = 0.1% and α = 27°: 1〜4 - time series captured during surface cooling (half of the wing surface image).

When the baffling grid was mounted, a spanwise temperature modulation similar to temperature modulation induced by Görtler-like vortices (Saric, 1994) was observed on the wing surface (Figs. 6-7). The results of experiments with LC coatings differed by working temperature range (δT: 3.5; 5 and 13°C) are presented in Fig. 6. It is seen that LC coating with more narrow operating temperature bandwidth clearly visualizes temperature effects of longitudinal structures. Similar vortex structures were revealed in boundary layers of other types. For instance, the flow pattern on the windward surface of wing observed in the present study was very similar to those observed in the case of a natural-convection flow over an heated inclined flat plate (Jeschke et al, 1998).

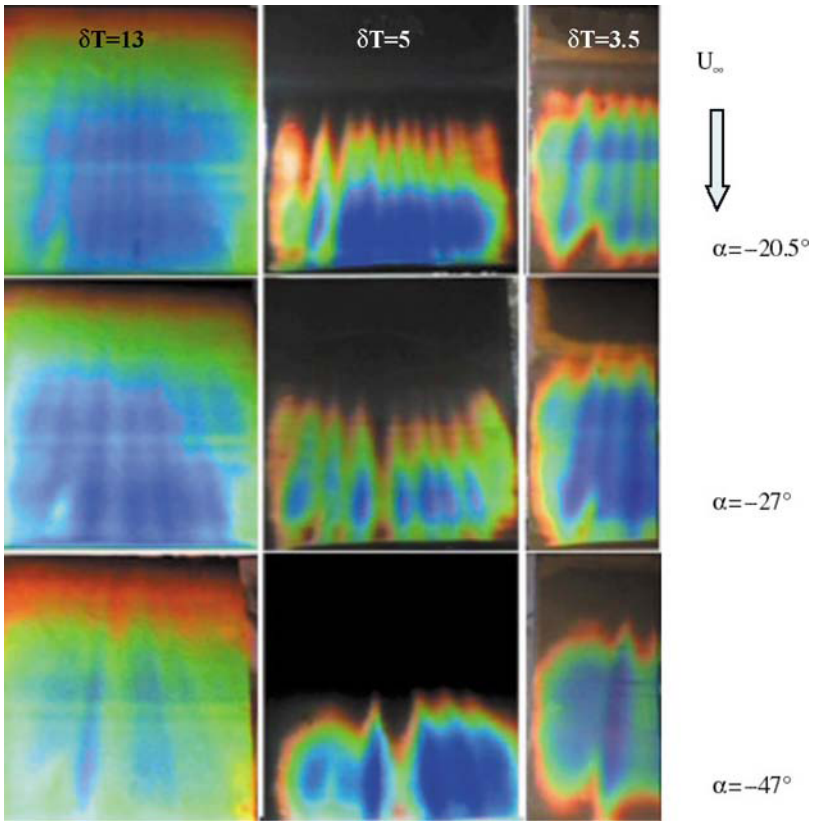

Fig. 6. Liquid-crystal visualization on the windward side at ε = 1% by LC mixtures with different temperature sensitivity δT = 13°, 5 and 3.5°C (the latter case- half image). α = −20.5, −27 and −47°.

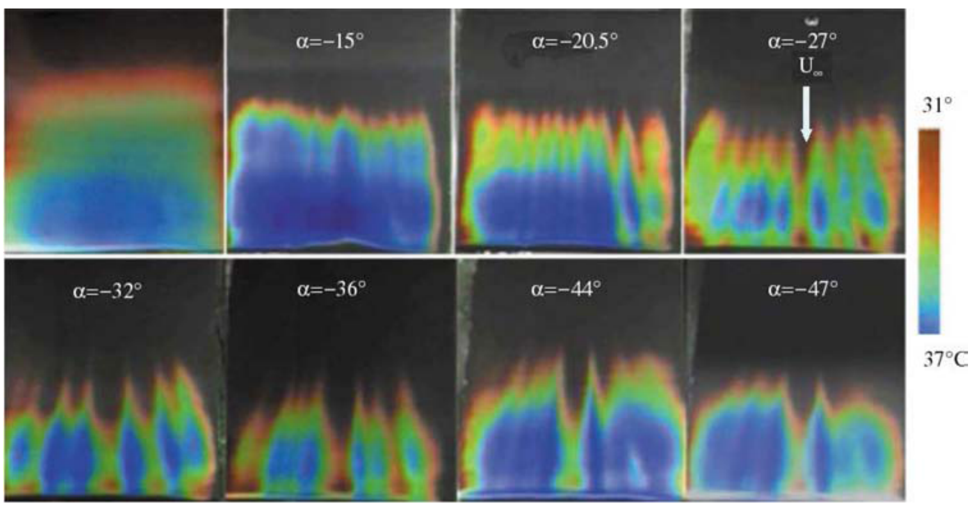

Fig. 7. Liquid-crystal visualization on the windward side at ε = 1% and various angles of attack.

It is known that Görtler vortices originate in laminar boundary layers due to an imbalance between centrifugal forces and the radial pressure gradient over a concave wall provided that wall curvature radius is much less than boundary layer thickness. Since the present experiments were carried out in a wind tunnel with an open working part, the free stream was deflecting substantially from the wing surface, i.e. the direction of the flow (streamlines) was approximately the same as it would be in the flow over a concave surface. It seems just the case in which Görtler vortices develop. However, without baffling grid LCT method using LC with $\delta T > 3.5^{\circ}$ did not permit to detect longitudinal structures in spite of the same streamline curvature.

Farther, in Fig. 7 the temperature distributions for angle of attack α from -15° to -47° are presented. In this figure it is seen that a number of the structures is greater at low angles of attack. Possibly, this fact is connected with more strong diverging of the free stream in open test section at the higher angles of attack and tip effects,

The sensitivity of the flow pattern to small variation of free stream turbulence was examined by locating the model at different distances from the grid. As the model was moving farther from the grid (at 198 mesh size), the total number of the longitudinal structures was found to change (Fig. 8).

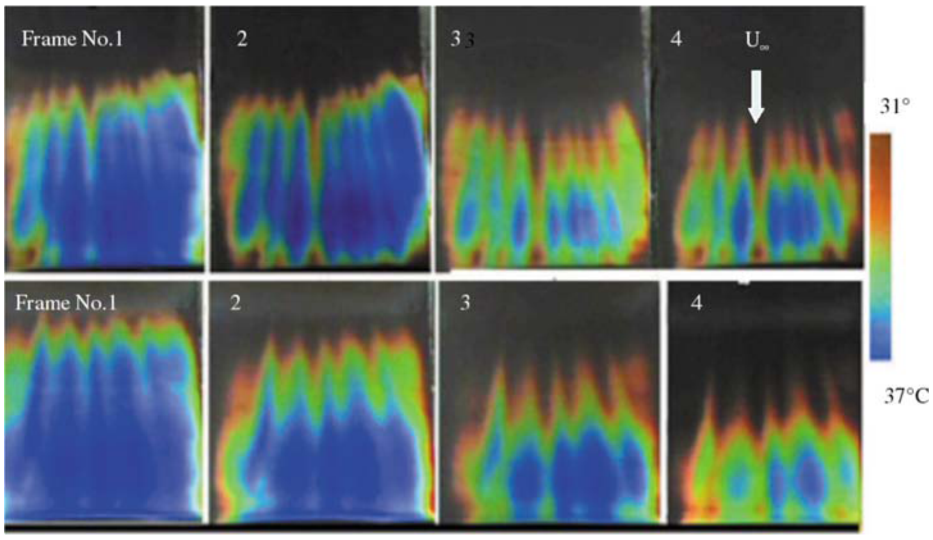

Fig. 8. Liquid-crystal visualization for various distance L from the model to the grid at ε = 1% and $\alpha = -27^{\circ}$: L = 146 mesh sizes (upper row), L = 198 mesh sizes (lower row). Movies 1〜4 captured during wing cooling.

4. Conclusion

Systematic data on the panoramic temperature distribution on the lee and windward sides of a symmetric airfoil wing were obtained by means of LCT method. It has been shown that the flow structure over the wing depends on free stream turbulence.

The stagnation region of the separation-bubble type was found near the leading edge of the wing on the lee side at increased free-stream turbulence under poststall angles of attack.

The large-scale stationary longitudinal vortices are originated over the wing windward surface. The number and sizes of longitudinal structures were found to be dependent on free stream turbulence structure, the angle of attack and tip effects.

Acknowledgments

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