Diagnostics of Boundary Layer Transition by Shear Stress Sensitive Liquid Crystals

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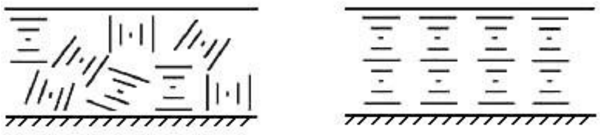
Abstract Shear stress diagnostics in aerodynamic tests can be performed using thin-film coatings based on optically-active liquid crystals (LC) which are sensitive to shear stress. These coatings do not change the model geometry and can be easily applied on the investigated surface including metal models. The method of selective reflection of the white light falling on the liquid crystal with a planar texture was used in this work. Four series of tests have been performed on metal models at subsonic and transonic flow velocities in the wind tunnels (WT) T-128 and T-103 (TsAGI). The last one series of tests that will be observed in detail was performed at Mach numbers M=0.78-0.79 and Re numbers Re=3x106, 4.5x106 and 4.8x106 in T-128 transonic wind tunnel. Using the method of shear stress sensitive liquid crystals visualization of laminar-turbulent transition, flow separation and shock waves was successfully performed. Experiments showed that liquid crystals are a promise for panoramic shear stress diagnostics.
Keywords: shear stress sensitive liquid crystals, laminar-turbulent boundary layer transition, wind tunnel tests, flow visualization

1 Introduction

Diagnostics of the boundary layer laminar-turbulent transition has an important role in the aircraft aerodynamics as the condition of the boundary layer effects on flow separations and aerodynamic characteristics of the aircraft, aerodynamic stability, efficiency of the engine operation and flight range. To recalculate the results of the wind tunnel tests to the conditions of the real flight it is also necessary to know the position of the laminar-turbulent transition on the model in wind tunnel. So the problem of laminar-turbulent boundary layer diagnostics is one of the key tasks of experimental aerodynamics.
The proposed method is used for shear stress diagnostics on metal models in wind tunnels and it does not need any special heat-insulating coatings. It allows visualization of the laminar-turbulent transition of the boundary layer, flow separations and shock waves and obtaining the whole image of the shear stress distribution on the investigated surface.
The key aspects of the method are choosing the optimal liquid crystal coating and providing shear stress visualization at the investigated surface at the observation angles defined by the windows in the walls of the wind tunnel test section.
The method of shear stress sensitive liquid crystals is well known but is rarely used in commercial tests.

2 Physical Basis of the Method

Such type of liquid crystals as cholesteric LCs is generally used for diagnostics of shear stress. The periodical helical structure of cholesteric LCs defines their ability to reflect the falling white light selectively [1]. At the fixed observation angle the LC layer in its temperature range of selective reflection seems to have one color which is defined by the helix pitch P. This pitch in its turn can be dependent to many factors: temperature and shear stress, for example. In our tests the cholesteric liquid crystals which are sensitive to shear stress and insensitive to temperature in the range of ΔT=(293-323)K were used.
Optical features of cholesteric liquid crystals appear only at definite molecular orientation in the LC layer relative to the model surface. Two textures of cholesteric LCs are practically used in aerodynamic tests. The first one is the focal-conic texture in which the long axes of the molecules are perpendicular to the surface plane or are not parallel to it in the general case and the helical axes are oriented chaotically. The second one is the planar texture in which the molecules are parallel to the surface and the helical axes are perpendicular to it (Figure 1).



a) b)

Fig. 1 Cholesteric LC textures: a) focal-conic, b) planar

Focal-conic texture is usually formed while spraying the LC coating perpendicular to the surface. In contrast to transparent planar texture which selectively reflects color the focal-conic texture has strong flare. Texture transition occurs under influence of shear (focal-conic texture transfers to planar texture). The image that appears after the flow influence on the focal-conic texture has memory properties due to the long-term relaxation. That's why this effect can be used to visualize the stationary flows in conditions of visual access absence [2].

The experimental method is based on registration of the optical response of the liquid crystals on the shear stress induced by the flow in the wind tunnel [3].

There are two main methods of performing tests using shear stress sensitive cholesteric liquid crystals.

The first method is based on texture transformation of cholesteric liquid crystals from focal-conic to planar under shear stress. Such process of texture transformation is irreversible. This method does not depend on the light source and observation angle as it is based on the time of color appearance. Calibration of liquid crystals in this case is easily performed.

In the second method which was used in the tests performed the liquid crystal mixture obtains planar texture at the beginning. This texture selectively scatters light with the dominant wavelength which changes under shear stress [4]. It is a reversible process as the dominant wavelength will return to its initial value when there is no shear stress. This technique is mainly used for visualization of shear distribution. There are some difficulties in using this method for quantity measurements because of strong dependence on light source and observation angle.

The most appropriate LC mixture for visualization is the one that changes its color in all visible color range (from red to blue) correspondingly to shear stress change in the whole range of τ_{min} - τ_{max}. Such mixtures provide maximal sensitivity of the method.

When the applied shear stress achieves some limit value the LC coating starts to flow at the model surface. In case of the decrease of the LC layer thickness the dominant wavelength of the reflected light does not change, it's only the intensity of the reflected signal which decreases as a result.

3 Model Preparation

Before applying the LC coating the investigated model surface should be black painted. Such painting is needed to decrease the amount of light reflected by the model surface and to increase thereby the contrast of the visualization image produced by light scattered by the liquid crystals. Black paint can be applied by spray or by brush. When this coating dries up the LC mixture can be applied by spray or by brush in different tests. The drying process takes nearly 20 minutes. The thickness of the black paint is approximately 20 μm and the total thickness of the coatings is about 40-50 μm. Therefore such thin layer does not change the model geometry.

The mixture of acetone and toluene should be used as a solvent of liquid crystals. That's why it is better to apply the LC coating by brush if it's possible to reduce the hazardous exhalations. And this fact also influences on choosing the black paint as it should not be dissolved by acetone or toluene and there should be no interaction between the paint and the LC solvent.

If the tests are performed by the method of texture transformation than the LC mixture should have the focal-conic texture. So it should be applied by spray or if it is possible it can be applied by brush and then heated up till it turns to isotropic liquid. Then it should be cooled down and the mixture obtains the focal-conic texture too. For such tests the model preparation ends at this stage.

If the tests are performed by the method of selective reflection in addition it is necessary to perform so-called initialization process when the LC coating dries up. The texture of the LC mixture should be transformed from focal-conic to planar. This process is performed by applying shear stress. If the LC coating is applied by brush this process performs automatically. But if the mixture is applied by spray the initialization can be performed by brush or even by finger as the response of the LC coating is the same.

4 Illumination and Registration Systems

The method of shear stress sensitive liquid crystals needs a measurement system which consists of two parts: the illuminator and the color camera.
The model is illuminated with the white light. The pulse illumination is preferred in conditions of the external lighting and the vibration of the model or/and photo-camera.
The spatial arrangement of the light source and the camera can be different. Three variants were investigated while performing tests and some of them were found acceptable. These variants were:

- The light source is down-stream the model, the camera is up-stream the model;
- The light source is above the model, the camera is up-stream the model;
- The light source is up-stream the model, the camera is above the model.

The first layout was found unacceptable due to the glare which was situated practically in the center of the investigated model surface and occupied its considerable part.
The second layout is recommended in literature [5] and the optimal observation angle (between the camera and the model surface) is considered to be equal to 30º with respect to LC sensitivity.
The third layout differs from the second one only in the interchange of the positions of the light source and the camera. The third layout is found to be the most attractive in respect to the perspective of the model observation and to the realization convenience, especially in wind tunnels with closed test sections. It is easier to arrange the light source than the camera up-stream the model.
While arranging the equipment according to the second and the third layouts the glare is situated at the front edge of the investigated model surface and does not considerably prevents the surface flow visualization. So the second and the third variants were considered to be acceptable and it was also found that the angle between the light source and the camera can vary in some neighborhood of 30º without considerable losses in LC sensitivity.

5 Earlier Test Results

Earlier in TsAgi three series of tests were performed. Two of those tests were performed at transonic flow velocities and one at subsonic flow velocities. In all the series of tests performed by the proposed method liquid crystal mixtures produced at the Institute of Theoretical and Applied Mechanics named after S.A. Christianovich (ITAM) in Novosibirsk were used.
The first experiment was performed in the transonic WT T-128 (TsAGI). The tests were performed at Mach numbers in range of M = 0.2-0.93. Stagnation pressure was P0 = 10^5 Pa. Vertical fin of a passenger plane was used as a test surface. The plane had a fixed angle of attack near α = 1.5º. Three different coating were tested while performing these tests. At the area of each of three used liquid crystal coating sample rows of the trips were mounted on the fin parallel to the leading edge before applying the LC coatings. The trips represent cylinders 0.2 mm height with 1 mm diameter which were applied with 2.5 mm pace by standard technique. The results of visualization of shear stress fields at two different Mach numbers M=0.2 and 0.4 are presented in the Figure 2. At Mach numbers M = 0.2 and 0.4 all three types of liquid crystal coatings showed their efficiency. However the viscosity of the upper coating was not sufficient and it flowed rapidly at the model surface even at these flow velocities. The other two coatings were efficient at all the researched regimes.

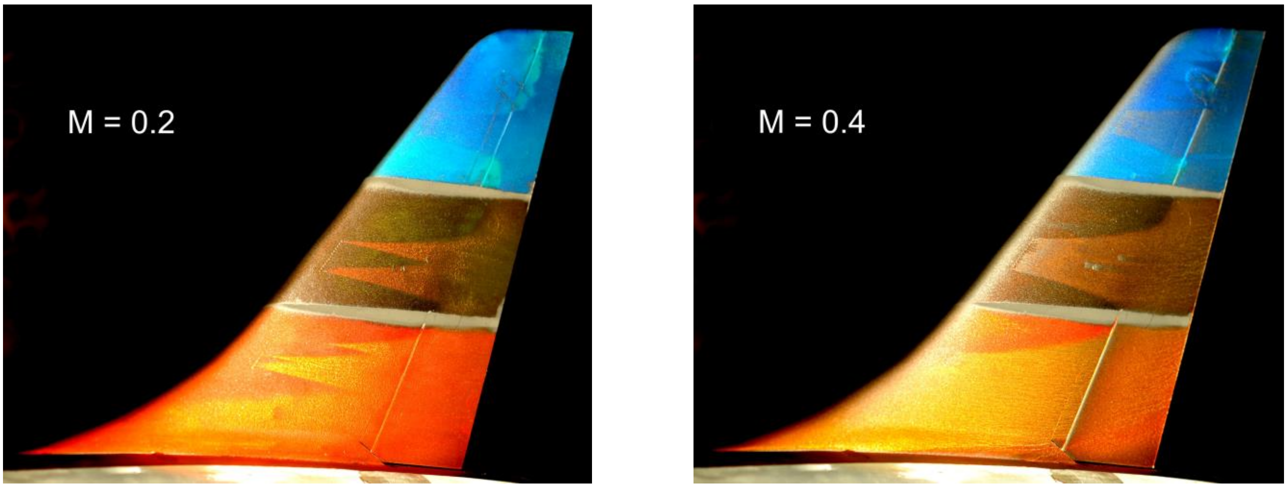


Fig. 2 LC visualization at the vertical fin at Mach numbers M=0.2 and M=0.4 in T-128 transonic wind tunnel (TsAGI)

The second experiment was performed at the subsonic wind tunnel T-103 (TsAGI) with an open test section. The flow velocity varied in the range of V = 10 m/s to V = 80 m/s. The method was investigated at a wing panel of a metallic fuselage-wing model. Two types of liquid crystal coatings were used while performing tests. Seven wind tunnel runs were made on the whole. The results of surface flow visualization at different flow velocities at the angle of attack $\alpha = 3^o$ are presented in Figure 3. At the flow velocities V = 10 and 20 m/s the transition was not detected. Apparently the flow is entirely laminar at these velocities. The camera was situated perpendicularly to the model surface and the light source was situated up-stream the model on the nozzle.

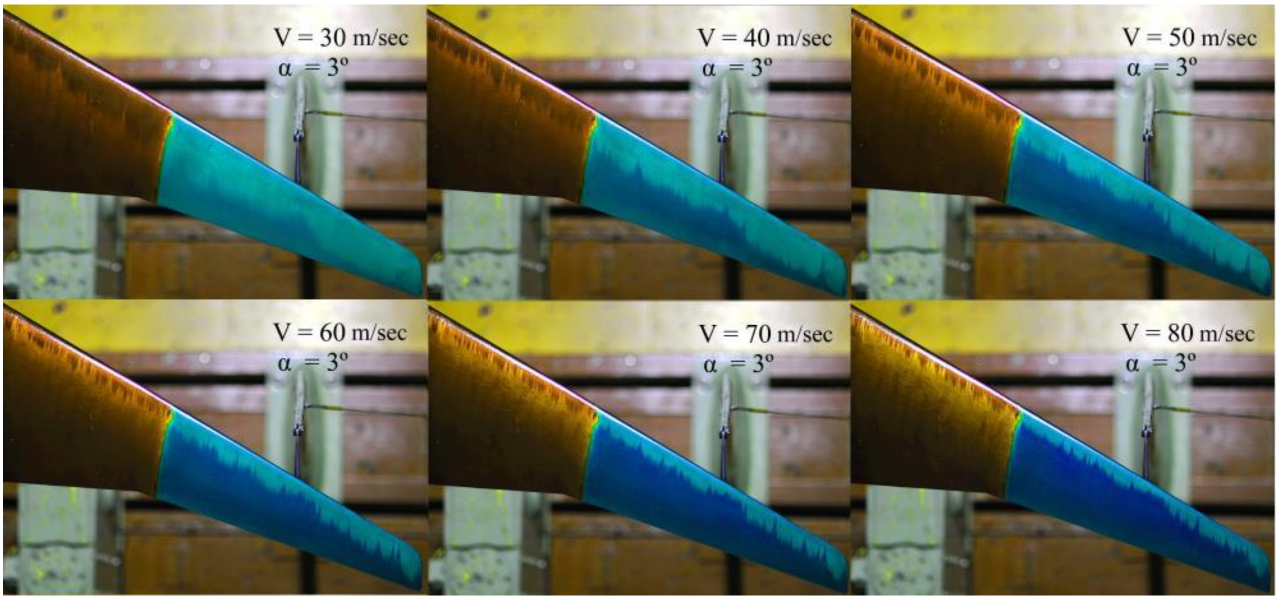
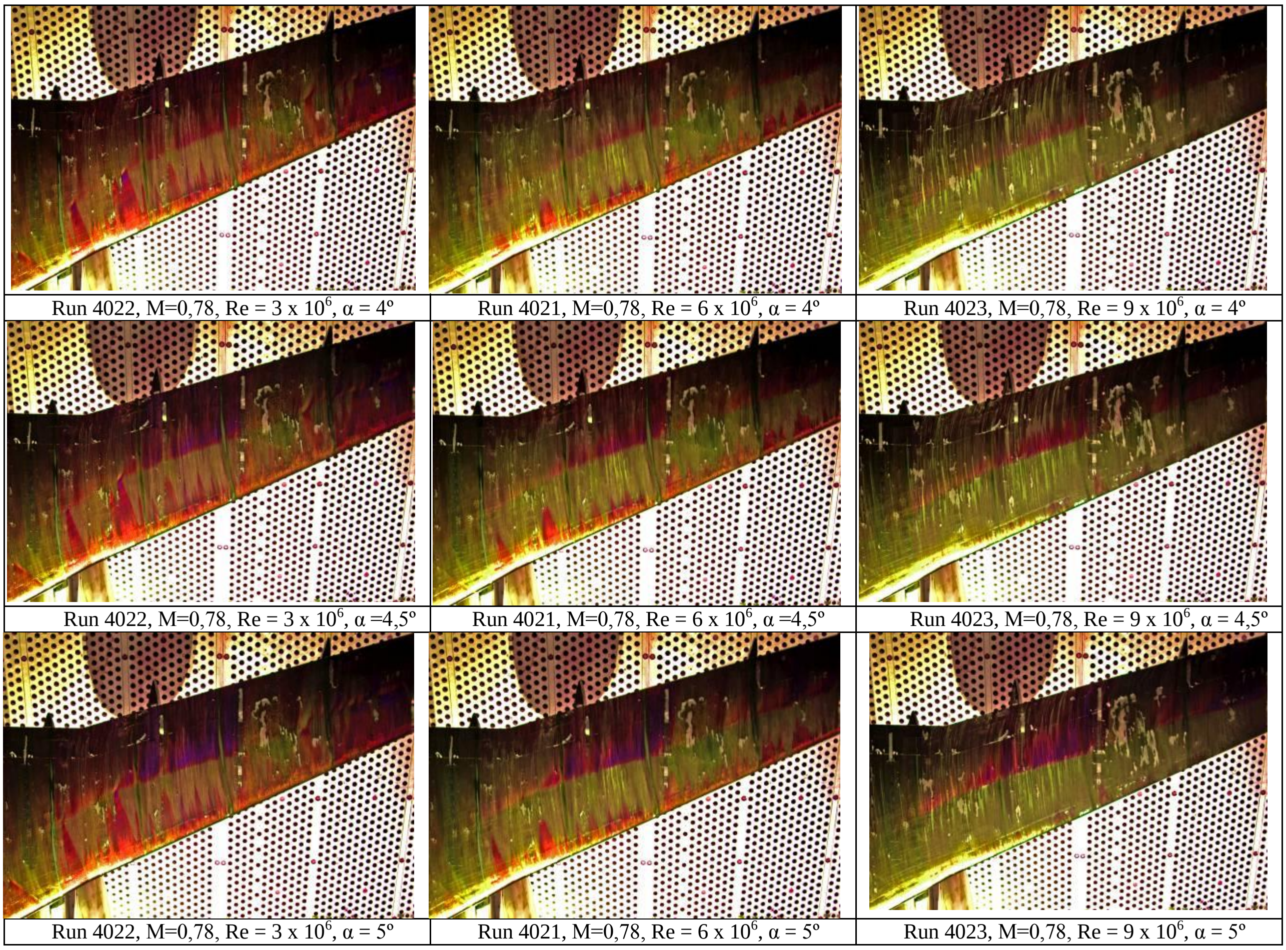


Fig. 3 LC visualization of surface flow at the metal wing panel at different flow velocities, angle of attack $\alpha = 3^o$ in T-103 subsonic wind tunnel (TsAGI)

The third experiment was also carried out in the commercial transonic wind tunnel T-128 (TsAGI). At this time the metal wing panel of a half-model of a passenger plane RRJ-95 was used as a model under test. Surface flow visualization was performed at Mach number M=0.78 and Re= $3x10^6$, $6x10^6$ и $9x10^6$. Angles of attack varied in the range of -4.5 to 7^o. Registration of images was performed by the camera which was situated perpendicularly to the investigated surface. The light source was situated up-stream the model. Visualization was performed using five different types of liquid crystals. During the performed tests 26 regimes of flow were investigated on the whole. Some of the results obtained are presented in Figure 4. At the angles of attack starting form $\alpha = 2.5^o$ the shock wave is clearly observed on the wing surface. The shock wave looks like an abrupt decrease of shear stress (color change). With the growth of the angle of attack the shock wave moves down the flow and its intensity increases. During the tests it was proved that the color of the LC coating sufficiently corresponds to the shear stress growth with the Reynolds number increase. Visualization of the laminar-turbulent boundary layer transition and the shock waves was successfully performed by all the types of liquid crystals.



Run 4022, M=0,78, Re = 3 x 10^6, α = 4º
Run 4021, M=0,78, Re = 6 x 10^6, α = 4º
Run 4023, M=0,78, Re = 9 x 10^6, α = 4º
Run 4022, M=0,78, Re = 3 x 10^6, α =4,5º
Run 4021, M=0,78, Re = 6 x 10^6, α =4,5º
Run 4023, M=0,78, Re = 9 x 10^6, α = 4,5º
Run 4022, M=0,78, Re = 3 x 10^6, α = 5º
Run 4021, M=0,78, Re = 6 x 10^6, α = 5º
Run 4023, M=0,78, Re = 9 x 10^6, α = 5º

Fig. 4 Visualization of surface flow at the metal wing by shear stress sensitive liquid crystals at different flow conditions in T-128 wind tunnel

6 Last Test Results

In the last series of tests the method of liquid crystals was used in WT T-128 on the wing-panel of the full model for the first time. Two types of supercritical airfoils of the perspective passenger plane with the sweep of $\chi_{1/4}$=15° and 25° were investigated. The tests were performed at transonic flow velocities (M=0.78 - 0.79) and Reynolds numbers Re=3*10^6 and 4.5-4.9*10^6. Angles of attack varied in the range of 0-6º. Stagnation temperature during the tests changed in the range of 36-57ºC. Under the influence of shear the coatings were slowly flowing but were still sensitive to shear. The thin layer of the coating was still efficient even after 10 minutes of WT operation at Re=5*10^6. Two types of liquid crystal mixtures were used in first two WT runs. But then it was decided to use only one of them as it showed better results.
The parameters of the performed wind tunnel runs are presented in Table 1.

Table 1 Flow parameters of the tests performed in the T-128 wind tunnel

Run No	M	Re	$T_{0b} \div T_{0f}$, ºC	α, º	Investigated wing	LC mixtures
3007	0.79	3.15×10^6	38.1-41.3	0.5-6º	No 1	(AVa)30Chl27, (AVa)30Chl30
3008	0.79	4.89×10^6	53.9-57	0.5-4º	No 1	(AVa)30Chl27, (AVa)30Chl30
3011	0.78	3.0×10^6	36.6-39.4	0-4º	No 2	(AVa)30Chl27
3012	0.78	4.55×10^6	42.4-43.9	0-5º	No 2	(AVa)30Chl27

Concerning the illumination system in the tests performed the illumination of the model was performed by «Integra Pro-1000» photo flash-lamp produced by “Hensel”. Pulse illumination is preferable in the conditions of external lightning and in case of the model or/and camera vibration. In the test section of WT T-128 the lighter was located up-flow the model in the upper part of the side wall. To register the color image of the model the digital color camera VS-CTT-11002-Color with the objective lens with 50 mm focal length produced by Nikkor was used. The camera was located in the optical window of the upper wall down-flow the model.

Example of the LC visualization is presented in Figure 5.

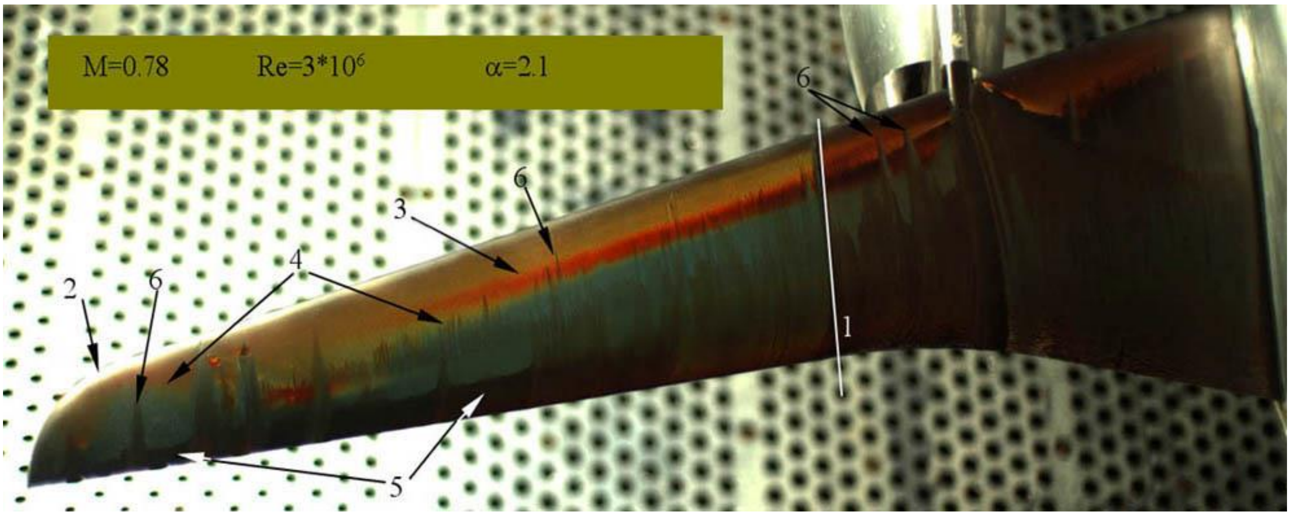


Fig. 5 Visualization of the flow over the wing-panel by the LC coatings method in WT T-128: 1 – border between two types of LCs, 2 – glare, 3 – laminar flow separation with the further reattachment of the flow (“bubble”), 4 – laminar-turbulent transition, 5 – flow separation zone, 6 – residual image of the previous flow regime (memory effect)

Two types of coatings were applied on the model; the border between two types is shown in the figure as a white line. As it was already mentioned the shear stress increase leads to the color change from red to blue, the return flow looks black. According to this, it is possible to interpret the test results. The red line along the leading edge of the wing can be seen in the image and it can be interpreted as the laminar flow separation from under the shock wave (“bubble”) with the further reattachment. After the shock wave the coating becomes blue-green and it can be interpreted as the transition to the turbulent flow. Near the back edge the coating looks black and it means the diffuser flow separation with the return flow. Unfortunately the coating has the memory effect and it is possible to see the structure (turbulent “traces”) on the wing which remained from the previous flow regime and it significantly complicates the interpretation of the flow image.

At the end of the wing the coating has a good range for the investigated flow (the color changes from red to blue-green) and it allows investigation of all needed flow conditions without flow interruption and model re-preparation.

7 Conclusion

The tests performed by the method of shear stress sensitive cholesteric liquid crystals showed that the test method of selective reflection of the planar LC texture allows getting the flow visualization of the boundary layer on metal models in a wide range of flow velocities. The method can be used at subsonic and transonic flow velocities. It means that these detectors can be effectively used for laminar-turbulent transition, flow separation and shock wave visualization.
Unfortunately the whole color range was far from being realized in all these tests. It means that coatings can measure much higher shear stress values but at the current flow velocities the coatings were flowing at the model surface. At the same time it is possible to say that efficiency of coatings is enough for passing the whole flow velocity range.
It is also possible to say that the future work will be connected with obtaining the quantitative distribution of shear stress by liquid crystals on metal models in wind tunnels. But it is a much more complicated task.

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