Main features of application of liquid crystal composites for the near-wall flow diagnostics

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Abstract. In the work the special aspects of panoramic temperature and/or shear stress diagnostics by liquid crystals are considered. Some metrological characteristics of two types of LC composites on the basis of cholesterics and nematics are discussed. The temperature and shear stress hue sensitivity are analyzed. The examples of application are presented.

1. Introduction
Visualization of near-wall flows takes a special place in aerodynamic experiments. Discrete sensors allow obtaining information in individual points, whereas visualization gives the full flow pattern. Today, visualization has become a new interdisciplinary field of science aimed at investigating phenomena by experimental and numerical methods.

The method of liquid-crystal (LC) coatings with a spiral molecular structure is widely used to analyze different flows [1 - 3]. This method is based on Wolf-Bragg diffraction on the spatial LC structure and variation of optical properties under the action of external factors. A thin LC layer on the studied surface does not introduce any disturbances in the boundary layer, so this method is especially convenient for express visualization of a panoramic pattern. At the same time, it serves to obtain the quantitative information on the panoramic distribution of the studied value and its variation during the experiment.

In the aerodynamic experiment, the LC spiral is simultaneously influenced by the temperature and mechanical shear inducing the skin friction shear stresses. Creation of panoramic temperature and shear stress sensors is related to the solution of the problem of separation of the LCs optical response to the temperature and mechanical shear. Thus, the requirements to the materials for temperature sensors and shear stress sensors are different. In the first case, the optical response of the temperature sensor should be independent of shear stresses, in the second case, the sensors must be low-dependent on temperature.

The purpose of this work is to consider the properties of the liquid-crystal materials and peculiarities of their utilization for the panoramic diagnostics of the near-wall flow structure in the aerodynamic experiment.

2. Setup, materials and data processing
The system of measurements and LC experiments processing includes three main components: the LC coating as a sensor, the system of lighting and data registration (2÷6 synchronized cameras for video recording of the LC optical response to external disturbances from different angular positions), and the software for the digital processing of color video records during the calibration or measurement processes.

To obtain the panoramic distribution of the temperature or shear stress on the model in the aerodynamic experiment, the studied surface with the LC coating is registered with a color video
camera. However, the video record does not allow having the distribution of the dominant wave length of selective reflection $\lambda_{\text{max}}(x, y)$, which is necessary for the calibration in respect to the studied parameters and digitalization of the LC optical response pattern. That is why it is necessary to have the quantitative data about the color, i.e. to determine the color coordinates of each point in a certain system of color coordinates.

The system of color coordinates HSI (hue $H$, saturation $S$ and intensity $I$) is used here for the digital processing of the color video records. Since LC are used, which reflection spectrum lies in the visible part of optical spectrum and features pure spectral colors, the hue $H$ is sufficient for the pattern calibration and digitalization.

Liquid crystals present a large class of compositions, predominantly organic ones, and the orientation order is a must feature of them [2]. Changing the LCs and percentage of composition, one can have the composite with the required characteristics. Cholesterol ethers and a number of saturated and unsaturated acids with some nematic liquid crystals LC1289 were used as initial materials in the work. Fig. 1 presents the LC composites with different bandwidth of the selective reflection $\Delta T = (3\div50) \ C$ and different temperature sensitivity of the hue $\Delta H/\Delta T$ up to 50 grad/C. In this case, the $\Delta T$ expansion results from the increased percentage of nematic liquid crystals (0\div60) weight % in the cholesterics mixture ABA45 (45% cholesteryl valerate and 55% cholesteryl nonanoate). Along with the temperature axis in Fig.1, the color gamut of LCs is shown for all mixtures.

Then, for better understanding of Hue value behavior, the dependences $\lambda_{\text{max}}(T)$ for two compositions 1 and 2 (0 and 10%) are shown.

Fig. 3 presents the hue dependence on the shear stress $H(\tau)$ measured in the green band of $\Delta T$ for the same two composites (0 and 10%). Analysis of Figures 1 - 3 shows that in the studied ranges of $T$ and $\tau$, these composites with high temperature sensitivity have different sensitivity to shear stresses. The composite 1 (ABA45) has high sensitivity both to $T$ and $\tau$, hence the 2D calibration $H(T, \tau)$ is needed for the digitalization of this mixture response. But second LC composition (ABA45+10% of nematic LC) is practically insensitive to shear stress.

Thus, taking the thermomechanical effect in pure LC into account, to gather the quantitative data on the required value, it is needed to have a set of curves $H(T, \tau)$ and evaluate the temperature or shear stress sensitivity of hue. It will allow choosing the optimal composite and minimizing the measurement error. The software must include respective modules.
Figure 1. The hue vs temperature dependence for ABa45 with (0÷60)% weight of nematic additives.

Figure 2. Dominant wavelength vs temperature for LC mixtures 1 (0) and 2 (10% NLC).

Figure 3. Hue vs shear stress for two LC mixtures (1 – $T_1=44^\circ C$, 2 – $T_2 = 27^\circ C$)
2.1. Liquid crystals for temperature diagnostics – polymer-dispersed LCs
To use liquid-crystal coatings for temperature measurements, they have to be protected from the mechanical shear. This task has been solved successfully by thermo-indicator films in which LCs are encapsulated into small polymer capsules. Polyvinyl acetate is used as the polymer matrix; it has high transparency both in the visible and IR ranges of the optical spectrum. The solution of LCs and polymer is imposed on a lavsan substrate. When the solvent evaporates, a film forms inside which the LC of a certain orientation are formed; they selectively reflect the light within the prescribed temperature range. The main characteristics of the developed thermo-indicators are: the working temperature range from –5 to +150°C; film thickness of 20÷30 µm; threshold sensitivity of 5×10^{-4} W/cm²; time constant of 0.2÷0.3 s; and thermal conductivity of (0.17÷0.20) W/m·deg.

When studying the heat transfer, the experimental procedure of liquid crystal thermography and result interpretation depend on the boundary conditions on the model surface, kind and character of the thermal load. The simplest case is realized at the constant density of the heat flux toward the studied surface. In this case, iso-color regions will correspond to the regions with the same specific heat flux. In long duration hypersonic wind tunnels, the boundary conditions with the constant heat-release coefficient often occur on the model surface. At the same time, taking the phenomenon complexity into account, it is necessary to check in each case the adequacy of the chosen mathematical model to the physical process under consideration. As a rule, the LC indicators with the low dynamic range are used for the analysis of subsonic flows. On the contrary, while studying the aerodynamic heating, this range must be maximal.

The technique of LC thermo-indicator utilization for the analysis of subsonic flows was tested under different conditions; see [5-7]. In particular, LC thermography was used to detect the region of maximal receptivity on the flying wing surface. Experiments were executed in subsonic wind tunnel T-324 of ITAM SB RUS [5].

Fig.4 presents the results of LC visualization of the flow pattern downstream the localized 3D roughness elements in the area of negative pressure gradient at free stream velocity of 15.1 m/s. Roughness height h = 0.98 mm, and diameter is 1.6 mm.

![Figure 4. LC visualization (a) and temperature map (b). V∞=15.1 m/s.](image)

2.2. Liquid crystals for shear stress diagnostics.
For shear stress diagnostic pure liquid crystals are used. Under different test conditions the diagnostics of the shear stresses may require both the low-temperature (5 ÷ 15C) LC composites and the ones for room and higher temperatures (above 100C). Thus the task was to develop the LC composites sensitive to the shear stresses within a certain temperature range but low-sensitive to temperature. The
diagnostic LC mixtures (binary, three- and multi-component composites based on cholesteric and nematic LCs) with different bandwidth of selective reflection $\Delta T$: $(1 \div 3) \, ^\circ C$, $(3 \div 7) \, ^\circ C$, $(7 \div 17) \, ^\circ C$ and $(\Delta T=50^\circ C)$ have been developed and studied. Their hue value in varying degrees depends on both temperature and surface shear stress. Therefore, for practical measurement of shear stress in the digital processing of their color images, it is necessary to apply 2D calibration of LCs.

An example of visualization of surface shear stresses by a thin-layer of pure liquid crystals with a wideband $(\Delta T= 50^\circ C)$ and low sensitivity to temperature is shown in Fig. 5. In the figure the example of visualization of the pattern of the subsonic flow around a step with the LC coating is presented. The step model is installed in the channel with the cross section of 120 x 80 mm, fixed with two screws. The experiments were carried out at two wall temperatures $T_w= 25$ and $34^\circ C$ and free stream velocity of $78 \, m/s$. The step height $h = 5 \, mm$, the width of pentagon base is 78 mm. The upper rib of the leading step edge has defects, and the surface is somehow rough. Within the studied range $T<35^\circ C$, this LC mixture is temperature insensitive, whereas $\Delta H/\Delta \tau \cong 2.2 \, \text{deg.} /^\circ C$.

![Figure 5](image)

**Figure 5.** Shear stress LC visualization at $T_w= 25$ and $34^\circ C$ (a, from top to bottom); Hue map (b); $V_\infty=78 \, m/s$. The arrow shows the freestream direction.

The LC visualization clearly reveals the characteristic peculiarities of the model and experiment geometry, for instance, the micro-vortices behind roughness elements on the step surface and leading edge rib. The pattern unsymmetrical shape is also evident; it is caused by the influence of different gap width between the step and the channel wall (the lower gap is wider). The areas in front of and behind the step which did not vary in their color, correspond to the flow separation areas.
The obtained shear stress distributions allow detecting the flow separation and reattachment lines, their shift versus the wall temperature, the area of flow recirculation on the step surface; varying level of the shear stress; the effect of screws and gaps between the step and channel wall; surface and leading edge quality. It is also evident that the 9°C change of T did not result in any essential change in the flow structure.

Conclusion
The paper discusses the metrological characteristics of LC composites based on cholesteric and nematic LCs. Liquid crystals composites have been developed to work in a wide range of temperatures from -5 to 150°C and shear stress up to 20 Pa. Dependences of LCs colorimetric optical response on temperature and shear stress H (T, τ) have been obtained. In an aerodynamic experiment, the choice of the type of LC coating is determined by the task. Polymer-liquid-crystal films that are not sensitive to shear stress are used to measure the temperature. If pure LCs are used to measure the panoramic distribution of shear stress, two-dimensional calibration H (T,τ) should be used in digital image processing. The developed materials and method of liquid crystal coatings was used in various aerodynamic installations and proved to be highly informative in the study of the structure of near-wall flows.

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