Journal of Applied Mechanics and Technical Physics, Vol. 43, No. 2, pp. 274–279, 2002

EXPERIMENTAL STUDY OF SUBSONIC FLOWS BY LIQUID-CRYSTAL THERMOGFRAPHY

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UDC 532.783

The physical basis of liquid-crystal thermography, which allows visualization and measurement of temperature and heat-flux fields, are expounded. An experimental technique and methods of obtaining quantitative results are described. Two approaches (monochromatic and chromatic) to interpretation of visualization data are considered. Results illustrating the possibilities of the method in an aerophysical experiment are given.

Introduction. In fluid mechanics, panoramic visualization of flows is a preliminary stage of each investigation of the flowfield by probing, which is extremely important. Visualization of the boundary-layer flow and determination of its gas-dynamic parameters are especially complicated because of their high sensitivity to small perturbations of the flow. All flow perturbations are known to be accompanied by a change in temperature in the boundary layer. Therefore, visualization of the temperature distribution near the wetted surface and its measurement allow identification of various structural features of the flow, such as the transition of a laminar flow to a turbulent state, separation and reattachment of the flow, effect of shock waves on the boundary layer, etc. Infrared (IR) and liquid-crystal (LC) thermography is traditionally used for nonintrusive panoramic visualization and temperature measurement on the model surface. Both methods allow simultaneous determination of the temperature and heat-flux distributions on the surface of a complex-shaped model in one experiment.

Optical effects in liquid crystals were first used in an aerodynamic experiment to visualize the transition of the boundary layer from the laminar to the turbulent state in 1968 [1]. Since that time, much progress has been achieved in further development of LC indicators and methods for their application in experimental aeromechanics [2–5]. The known methods of liquid-crystal thermography (LCT) were modified and novel techniques have been developed lately [6–12] owing to improvement of measurement equipment and creation of new LC materials. The LCT method is currently characterized by a good spatial resolution and temperature sensitivity, which allows one to use experimental data for verification of numerical models of complex flows.

Physical effects in liquid crystals are considered in the present paper, and the technique of an aerodynamic experiment with the use of liquid crystals is described. Two approaches (monochromatic and chromatic) to interpretation of visualization data are considered. The capabilities of the LCT method are illustrated by results on the flow structure obtained for a low-aspect-ratio wing in a subsonic flow.

1. Optical Properties of Thermochromic Liquid Crystals. The temperature measurement with the use of liquid crystals is based on the effect of selective scattering of light on a periodic structure of cholesteric liquid crystals. In these crystals, the molecules are packed in layers. Within each layer, the molecules tend to align parallel to a certain common axis described by a unit vector called the director. In passing from one layer to another, the director turns at a small angle. As a result, a layered spiral texture with a certain spiral pitch is formed; it is called the planar texture. Being illuminated by white light, this texture selectively reflects light, similar to a diffraction grating. In this case, the Wolf–Bragg condition is satisfied, i.e., in the case of normal incidence of light, the wavelength with the maximum intensity of reflection λ_0 is approximately equal to the spiral pitch. For many cholesterics, the spiral pitch is $p = 400$–1000 nm; therefore, λ_0 is within the visible light range. Since

Institute of Theoretical and Applied Mechanics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 43, No. 2, pp. 122–128, March–April, 2002. Original article submitted June 29, 2001.

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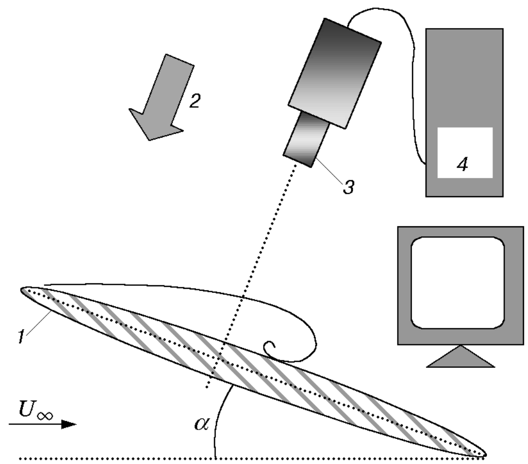

Fig. 1. Optical scheme of measurement and calibration: 1) model (or thermowedge for calibration); 2) source of light; 3) camera; 4) computer.

cholesteric liquid crystals are a labile medium, an arbitrary external action (change in temperature or mechanical shear) changes the spiral pitch, which is accompanied by a change in the wavelength and intensity of selective reflection, i.e., the color of the crystals. The dependence of the color of cholesteric liquid crystals on temperature allows one to obtain a panoramic image of the temperature field on the surface under study.

2. Liquid-Crystal Thermography Technique. The liquid-crystal application is comparatively simple. Along with some specific features in each particular case, there are certain common conditions. First, it is necessary to know approximately the temperature range where the LC coating should operate. Second, the LC coating should not disturb the temperature field of the examined surface, i.e., the total heat capacity of the medium tested should be greater than the heat capacity of the LC coating. Third, the rate of variation of the temperature field should be smaller than the time constant of the cholesteric liquid crystals used.

In aerodynamic experiments, the LC coating is simultaneously affected by temperature and skin friction. To protect liquid crystals from mechanical shear, a small amount of varnish or glue is added to them. A more reliable method of protecting LC from mechanical actions is encapsulation of liquid crystals into a polymeric matrix [4]. The choice of the polymeric matrix and encapsulation technology are determined by test conditions. The material resulting from encapsulation of liquid crystals can be obtained in the form of a film or separate capsules in an isotropic medium. The main characteristics of LC thermoindicators are the bandwidth of operating temperatures of a given indicator, the dependence of the wavelength of selective reflection of light (color) on temperature $\lambda = f(T)$, which is called the color–temperature characteristic, and also the ratio $\Delta\lambda/\Delta T$ that characterizes the temperature sensitivity. These characteristics are determined by the composition of the LC mixture. There are mixtures with a bandwidth of operating temperatures from 0.02 to 50°C within the temperature range from -30 to 250°C.

The choice of the LC coating (liquid crystals in a free form or encapsulated into a polymer) is determined by the flow velocity in the experiment. It was found that the color of liquid crystals in a free form is not significantly changed under the action of shear stress up to flow velocities of 10–20 m/sec. For higher flow velocities, the error in temperature measurement may be rather significant. Therefore, it is reasonable to use liquid crystals encapsulated into a polymer in high-velocity facilities. In this case, however, it is necessary to take into account thermal inertia of film thermoindicators. Depending on the film thickness and heat-transfer conditions, the thermal inertia index — time constant may reach 0.05 sec.

Passing through a cholesteric LC film, light decomposes into two waves, one of them is selectively reflected (exactly this wave characterizes the LC coating color), and the other passes without changes. The latter has to be absorbed, which is ensured by applying a thin layer of a black paint onto the surface under the cholesteric LC coating. It is important that the paint is not dissolved in the organic solvent used to apply the LC coating. After that, the LC coating is deposited. If a film is used and the surface shape is close to a plane, the film is glued. A complex-shaped surface is coated by a mixture of liquid crystals and a polymer or glue in the solvent by means of spraying. The choice of the solvent and the ratio of liquid crystals and the solvent are determined by the solubility of components and viscosity of liquid crystals. The optimal thickness of the coating is 20–30 μm.

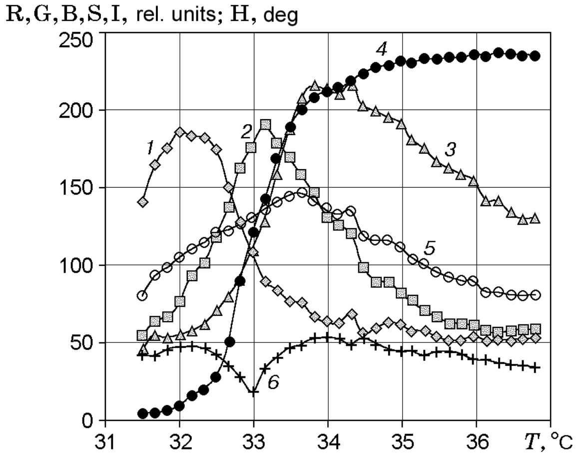

Fig. 2

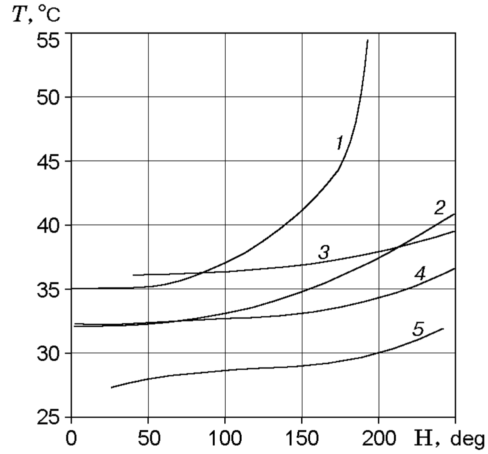

Fig. 3

Fig. 2. Typical dependences of the light coordinates R, G, B, H, I, and S on temperature: curve 1 refers to R, 2 to G, 3 to B, 4 to H, 5 to I, and 6 to 100S.

Fig. 3. Color–temperature characteristics of liquid crystals with different widths of the range of selective reflection: $\Delta T = 15$ (1), 7.8 (2), 3 (2), 4 (4), and 2.8°C(5).

The liquid crystals should be calibrated under geometric and illumination conditions used in the experiment. To weaken the angular dependence of selective reflection of cholesteric liquid crystals, the illumination and observation directions are chosen to be close to normal or are registered exactly for digital correction. The calibration is usually performed using a thermowedge with a linear temperature distribution on the surface controlled by thermocouples. The layout of registration and calibration is shown in Fig. 1.

3. Image Registration and Processing. To measure the temperature distribution, it is necessary to measure the wavelength corresponding to the maximum intensity of selectively reflected light at each point of the surface. Spectral instruments designed for this purpose are inconvenient under conditions of an aerodynamic experiment. If a video record or direct input of the image into the computer is used for registration, the spectral analysis can be reduced to analysis and digital processing of the image. Depending on the optical scheme of registration and calibration, all the existing methods of temperature measurement with the use of liquid crystals can be divided into two groups: methods with registration of the signal of intensity of selective reflection of monochromatic light and methods with registration and processing of the full color TV signal. We consider both methods in more detail.

3.1. *Methods with Registration and Digital Processing of a Monochromatic Image.* These methods include spectrozonal filtration and the method of fringes [6]. For temperature measurement from mono- and achromatic images, methods are developed based on spectrum decomposition by optical light filters, i.e., filtration, or using one or several sources of monochromatic radiation. In the first case, up to 20 frames are recorded to determine the position of the maximum of selective reflection of light of a certain wavelength, and each frame is registered through a certain light filter. Being highly accurate, this method requires a significant memory and speed of computational equipment. The duration of implementation of this method makes the study of unsteady processes impossible.

To overcome these drawbacks, the method of fringes was developed, which can be used instead of filtration for some problems and which allows one to study both steady and unsteady processes without being too expensive. In this method, the examined surface is illuminated by a light beam spatially modulated by straight-line regular fringes. With the help of a prism, the image of the fringes is decomposed into a spectrum along the coordinate corresponding to the direction perpendicular to the direction of these fringes. If the surface temperature is nonuniform, the position of the fringes for different wavelengths is different. Based on the shift of the fringes, one can measure the temperature field in one experiment, but the spatial resolution of this method may be insufficient for some problems.

3.2. *Methods with Registration and Digital Processing of a Color Image.* The optical response of liquid crystals is usually registered by a CCD (charge coupled device) camera with a sensor operating on the principle of charge coupled devices (CCD matrices). Individual frames are captured by interfaces, where the analog TV signal is

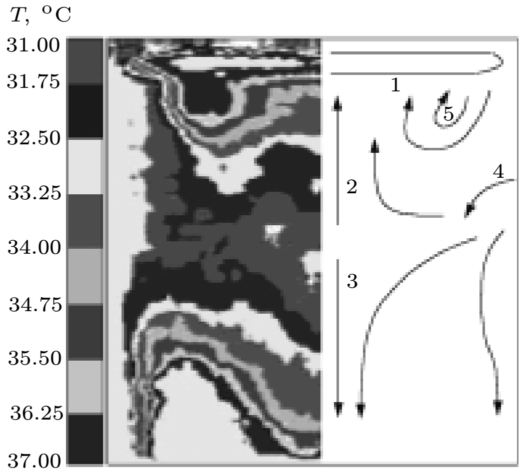

Fig. 4

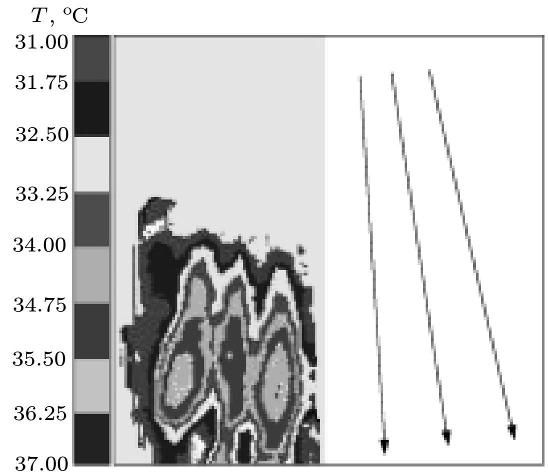

Fig. 5

Fig. 4. Chart of temperature distribution on the leeward side of the wing (left) and flow pattern (right) ($\alpha = 27°$, $\mathrm{Re}_c = 0.176 \cdot 10^6$, and $\varepsilon = 1\%$; flow direction from top to bottom): 1) stagnation region; 2) reverse flow region; 3) turbulent boundary layer; 4) tip vortices; 5) vortex focus near the leading edge.

Fig. 5. Chart of temperature distribution on the windward side of the wing (left) and flow pattern (streamwise vortices are indicated by arrows) (right) ($\alpha = 27°$, $\mathrm{Re}_c = 0.176 \cdot 10^6$, and $\varepsilon = 1\%$; flow direction from top to bottom).

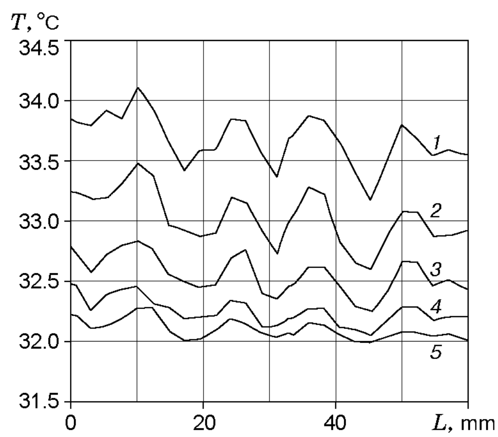

Fig. 6. Temperature variation in the spanwise direction L on the windward side of the wing ($\alpha = 27°$ and $\varepsilon = 1\%$) versus time for $t = 0$ (1), 4 (2), 8 (3), 12 (4), and 16 sec (5).

transformed into a digital form [red (R), green (G), and blue (B) components] and is stored in a video buffer. Thus, the temperature measurement reduces to color measurement (colorimetry) [13]. The process of color measurement consists in determining the coordinates of a point in the plane of colors in some colorimetric coordinate system. Therefore, all methods of interpretation of color images of LC thermograms are mainly distinguished by the chosen basic colorimetric system. The linear RGB system used in color TV is a Cartesian coordinate system constructed in accordance with the three-component theory of color vision. Since cholesteric liquid crystals reflect pure spectral colors, this model is not perfect for exact identification of color. Thus, a nonlinear HSI system was proposed for color measurement, where the color is determined by hue (H), saturation (S), and intensity (I) [11, 12]; the algorithm of RGB → HSI transformation is rather simple [13].

Typical dependences of the color coordinates R, G, B, H, S, and I on temperature are plotted in Fig. 2. As the temperature changes, the hue H, in contrast to the coordinates R, G, and B, changes monotonically; therefore, the dependence H(T) can be used for calibration and temperature measurement. The range of pure spectral colors is H $\leqslant 240°$. The mixed magenta corresponds to H = 240–360° (range of undetermined hue). To determine the color more exactly, one has to take into account the value of saturation S.

Figure 3 shows the typical calibration dependences H(T) for LC thermoindicators with different widths of the range of selective reflection ΔT. The temperature sensitivity of the LC coating at different sectors of the optical range of wavelengths is different and may reach 0.01–0.16°C with the hue varied by 1°.

The effect of various factors, such as the nonuniformity of illumination over the image field, aperture diameter of the iris diaphragm, thermal hysteresis, etc., was studied in a test series with LC coatings with different characteristics [14]. It was found that the calibration dependence H(T) is little sensitive to the action of the above factors, which is one of the advantages of the HSI basis in digital processing in LCT. Further improvement of the method is possible by introducing a second (angular) variable into the calibration dependence and/or using recording from different aspects. Taking into account these factor allows one to minimize the error of the measurement method and to use the high temperature resolution of liquid crystals to the maximum extent.

4. Example of LCT Application in an Aerophysical Experiment. A panoramic distribution of temperature and an averaged pattern of the near-wall flow were obtained by the LCT method in the flow around wings with aspect ratios $b/c = 0.87$ and 2 in a wide range of regime parameters [10]. The data available in the literature on visualization of the flow structure at low subsonic free-stream velocities were obtained by tuft or oil-film methods mainly for the leeward side of the wing.

Figures 4 and 5 show the measurement results on both sides of the wing for $b/c = 0.87$ obtained using an LC film with the bandwidth of selective reflection $\Delta T = 31$–37°C for an angle of attack $\alpha = 27°$ beyond stalling and the chord-based Reynolds number $\mathrm{Re}_c = 0.176 \cdot 10^6$. The wing model examined had a symmetric profile with a 16 % maximum relative thickness. The experiments were performed for an elevated level of free-stream turbulence $\varepsilon = 1\%$. As was expected, a separated flow is observed on the leeward side of the wing (see Fig. 4). On the windward side, there is a stationary system of streamwise vortices (see Fig. 5), which is absent for $\varepsilon = 0.1\%$. These streamwise vortices cannot be visualized by the oil-film technique. The presence of a system of streamwise vortices is confirmed by hot-wire measurements. Similar structures are formed on the wing with the aspect ratio $b/c = 2$, an asymmetric profile (the windward side is almost flat), and 15% maximum relative thickness. The spanwise variation in temperature on the windward side of the wing is plotted in Fig. 6 versus time for $x = 0.5c$ and Reynolds number $\mathrm{Re}_c = 0.176 \cdot 10^6$. In this case, the use of liquid crystals allowed visualization of temperature differences of 0.5°C and smaller, which are caused by specific features of the flow structure.

Conclusions. Unique optical properties of cholesteric liquid crystals, improved experimental methods, and digital processing of video images allow panoramic visualization and measurement of the temperature distribution on the surface.

The approaches developed are applicable for a wide range of problems on the fine structure of flows and also problems of heat transfer, heat control, or control of the model position in the flow, including investigations of some unsteady regimes.

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