Liquid Crystal Thermography (LCT). State of the art and application in aerodynamics

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Abstract
An overview of studies performed at ITAM SB RAS and aimed at the development and use of temperature-sensitive liquid-crystal composites in aerodynamic tests is given. Basic properties and characteristics of liquid-crystal materials are described. Results of a thermographic investigation of the near-wall structure of subsonic and hypersonic flows around bodies and also effects due to various boundary-layer perturbations are reported.

1. Introduction

Visualization of the flow and temperature fields on the surfaces of models still remains an important problem since, with the rapid progress in computational methods and computing facilities, a need has arisen in reliable experimental data for validation of theoretical models. Full-field flow visualization is a preliminary step in any experimental study of a flow field based on the use of probe methods. For instance, in two-dimensional (2D) cases, flow visualization tests make it possible to establish two-dimensionality of the flow pattern and identify flow features on the model surface. In three-dimensional (3D) cases, the examined flow structure provides a replicated surface picture of the complex 3D flow, allowing identification of critical points and lines (foci, saddle points, convergence/divergence lines, detachment and re-attachment points, etc.) on the surface.

Temperature-sensitive paints (TSPs)[1, 2], liquid-crystal (LC) thermography[3, 4], and infra-red (IR) thermography[5] are the main panoramic methods intended for visualization and heat-transfer studies in aerospace sciences. All techniques have been extensively used for a long period and still offer much potential as they allow registration of the temperature distribution over the model surface in a single test. Application of PC-based digital grabbing of temperature fields for subsequent data analysis allows one to obtain global quantitative data. At present, LCT and IRT techniques have gained more widespread application owing to high spatial resolution and high temperature sensitivity. Any method has advantages and disadvantages. A disadvantage of IR thermography is that an optical window made of a material transparent to IR radiation is required in experimental setups with a closed test section. The model should have high emittance. The accuracy of IR thermographic data can be deteriorated if spurious signals from external heat sources interfere with the useful signal. The angular dependence of the measurement results should be minimized both for IRT and LCT. LC indicators have a narrower range of working temperatures, but the disadvantage can be eliminated in tests with high temperature gradients by superposition of different mixtures, by using LC mixtures with two working temperature intervals, or digitally, by image superposition. LC indicators are not toxic, possess a high sensitivity to temperature, and good reversibility of the color picture, and can be repeatedly used to perform full-field visualization tests and measurements.

In aerodynamics, the use of the LC method dates back to Klein.[3] Digital image processing systems have enabled rapid progress in solving various LC-thermometry problems.[6-7] Since then, reported studies in which the LC method was used and the potential of the method was demonstrated has increased in number tremendously.

Briefly, the evolution and state-of-the-art technology of LC thermography include:

- progress in the LC materials (encapsulating LCs, LC with “memory,” LC coating with two different intervals of working temperatures[8], etc.)

- development of experimental procedures adapted to particular experimental setups and conditions (steady-state and transient LC thermography [9]), combined use of Particle Image Velocimetry (PIV) and LCT[10] , etc.)

- various optical schemes for image registration (spectral filtration, fringe method, intensity time history registration , true-color pattern registration[11-13], etc.)
- new calibration methods (principles and instrumentation) aimed at improving the measurement accuracy (successive isothermal/gradient method combined with colorimetric analysis, statistical methods using neural network algorithms, etc.)[12-18].
- novel algorithms for data reduction and correction adapted to particular problems; extraction of visualized data from full-field images (using analytical solutions of the heat-conduction equation, recent achievements in solving well-posed inverse boundary-value problems in heat transfer, image superposition, wavelets, etc.)

At ITAM, LC coatings have been produced, examined, and used since 1970[19]. The LC method has been adapted to many wind-tunnel facilities used at ITAM including
- small subsonic wind-tunnel facility MT-324, presenting a closed-layout wind tunnel operated with closed or open throat. The free-stream turbulence level is about 0.1%;
- subsonic low-turbulent (<0.04%) wind-tunnel facility T-324;
- hypersonic blow-down wind tunnel T-326 of the ejector type with exhaust to atmosphere;
- hypersonic nitrogen wind tunnel T-327.

2. Liquid Crystal Thermography: State of the art (short review).

2.1. Thermosensitive LC materials

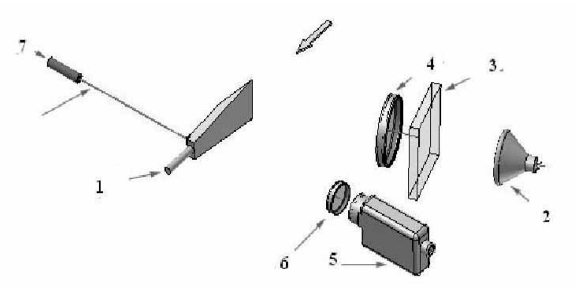
At ITAM, considerable experience has been accumulated in the field of structured LC materials. Liquid crystals are organic compounds in a state of matter intermediate between an isotropic liquid and a crystalline solid [2, 20]. For temperature measurements by LCs, selective reflection of light from the periodic structure of a cholesteric LC is used. Such an LC coating placed on the surface under study changes its color from red to violet when the temperature is increased. The thermal indicators are cholesteric LCs (ChLCs) or chiral nematic liquid crystals (NLCs), either in their pure or encapsulated form. The unique optical properties of the liquid crystals, namely, their high sensitivity to external effects, find wide application in the development of new diagnostic methods in aerodynamic experiments. The maps of temperature distributions produced with the help of liquid crystals allow one to investigate details of the flow structure near the surface and to develop methods of controlling this structure.

In aerodynamic experiments, an LC coating experiences a simultaneous action of temperature and shear stresses. To protect the LC against mechanical shear, a small amount of a lacquer or glue can be added to the LC composition. Another, more reliable method is encapsulation of the LC into a polymeric die. The choice of the polymeric die and encapsulation method is dictated by the experimental conditions for which the LC is intended. The final material can be obtained either in the form of a film or in the form of dispersed LC capsules suspended in an polymer[19-22]. The main characteristics of LC thermal indicators are the dynamic temperature range, normally understood as the interval of working temperatures; the temperature dependence of the selectively scattered wavelength, called the color-temperature characteristics; and the ratio $\Delta\lambda/\Delta T$, defining the temperature sensitivity. At ITAM, polymer-encapsulated CLC film coatings have been developed [20-24]. Such coatings render the LC material insensitive to shear stress, thus, making it more suitable for visualization of temperature fields. The color-temperature characteristic of encapsulated LC depends on the LC mixture. Mixtures developed at ITAM have a dynamic temperature range of 1.5 to 20° at temperatures ranging between −15 and 250°C, including compositions with two intervals of working temperatures[7]. The thermophysical characteristics of such LC coatings (thermal conductivity λ = 0.18÷0.25 W/m K, thermal diffusivity $a = (3 \div 4)\times10^{-7}$ m^2/s, and satisfactory adhesion to many materials) permit their use in domestic applications and in thermophysical researches.

The choice of a particular LC coating (either in pure or polymer-encapsulated form) is dictated by the flow velocity. Studies showed that pure LCs are incapable of displaying considerable color changes when experiencing air-flow-induced shear stresses up to flow velocities of 10÷20 m/s. Higher flow velocities may result in substantial inaccuracies in temperature measurements. That is why, in the case of high-velocity flows, polymer-encapsulated LCs are more preferable for use. In addition, the thermal response time of LC indicators has to be taken into account. Depending on the film thickness and LC properties, the response time can amount to more than 0.03 s, while the re-orientation time of pure LCs is one order of magnitude shorter [8, 25]. We mainly use encapsulated ChLCs sensitive to temperature and insensitive to shear stress or, vice versa, ChLCs sensitive to shear stress and insensitive to temperature. The model preparation for testing in hypersonic flows differs from that in the case of subsonic flows. Since thinner LC coatings are required in the case of hypersonic flows, the spray method is normally used to apply the LC coating onto the surface.

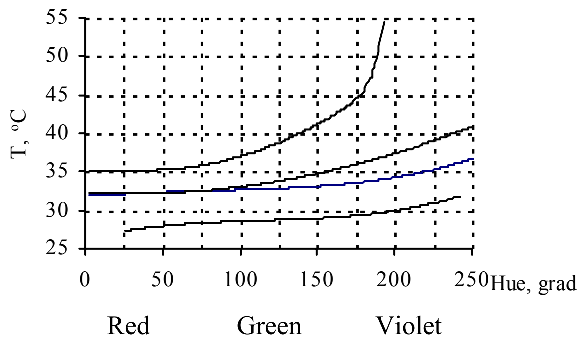
2.2 Calibration, recording, and interpretation of the LC optical response

A thermal indicator coating can be calibrated on a special bench; to improve the accuracy, however, it is more preferable to perform calibration tests under actual wind-tunnel conditions. The effect of the LC angular dependence can be reduced either by choosing the illumination and viewing angles close to the surface-normal direction or by accurately registering these angles for subsequent digital data correction. Various calibration procedures used in LC thermometry are described[13-16]. We routinely use two static calibration procedures, the successive isothermal method (using a thermostat) and the gradient thermocline method, combined with colorimetric analysis and thermocouple measurements. Since some LC mixtures are characterized by a hysteresis[26], calibration tests have to be performed with allowance for the direction of the thermal process under study. For heating processes, it is necessary to use a calibration curve obtained on a sample under heating, whereas for cooling processes, on a sample under cooling. Depending on the registration scheme, the registration methods are subdivided into the spectrozonal method, colorimetric method, and fringe method. In all cases, for good reproduction of color, a white-light source or video camera white balancing is required. Models made of heat-insulating materials or metals may be used. A thermal insulator used to make the model should have thermal characteristics close to those of the LC coating. Metallic models have to be covered with an additional heat-insulating coating or heat conduction should be corrected by any other way. At subsonic velocities, the temperature field on a preliminarily slightly overheated model, undergoing cooling under the action of the approaching flow, is visualized. Figure 1 shows the registration scheme and typical calibration curves. The LC temperature sensitivity depends on the temperature itself; typically, it decreases with increasing temperature.



1- model, 2 - light source, 3 - filter,
4,6 – crossed polarizers, 5-camera, 7- laser.

a)



b)

Figure 1. Experimental setup (a) and typical calibration curve (b)

After LC visualization, the visualized data have to be interpreted. Here, the fact must be taken into account that the heat-flux density vector is directed along the normal to isotherms, and the length of this vector varies in proportion to the local temperature gradient. Hence, the lower the heat-flux rate, the greater the distance between the isotherms in the isotherm-normal direction. For a thermally insulated model, it is normally assumed that the change in the heat-flux rate from one point to another is negligible, whereas this change along the normal to the surface is defined by the local structure of the near-wall flow.

3. LCT application in aerodynamics

3.1. Visualization of the near-wall structure of subsonic flows

During changes in the flow structure at subsonic flow velocities, small temperature gradients take place on the model surfaces. Such gradients can be successfully visualized due to high temperature sensitivity of LC coatings.

Some studies have been performed, aimed at investigation of the subsonic flow structure near the surface of straight and swept wings [27, 29]. Note that previously reported visualization data for low subsonic velocities were obtained using tufts or oil films and, for the main part, for the lee side of the wing. An experimental study of wing flows involves a broad range of problems concerning the influence of external disturbances on the flow structure in the wall layer. In particular, to date the effect of an enhanced free-stream turbulence level on the boundary-layer flow has been examined in detail only for the flat-plate flow. No such studies were made for the lower, windward side of the wing because it was assumed that, due to the favorable pressure gradient, the wing flow always remains non-separated and laminar, and the free-stream perturbations that enter the boundary layer decay there. However, data obtained by the present authors show that, under enhanced free-stream turbulence, well-ordered longitudinal vortex structures may arise on the windward side of the wing [27]. We examined the flow around a model of a rectangular wing with a symmetric airfoil (relative thickness 15%; chord length 232 mm). Visualization data for the boundary-layer flow over the lower half of the windward side of the wing installed at large supercritical angles of attack in a baffled flow with a turbulence level of 1% are shown in Fig. 2. For comparison, the first visualization frame shows data obtained for the wing installed at a zero angle of attack.

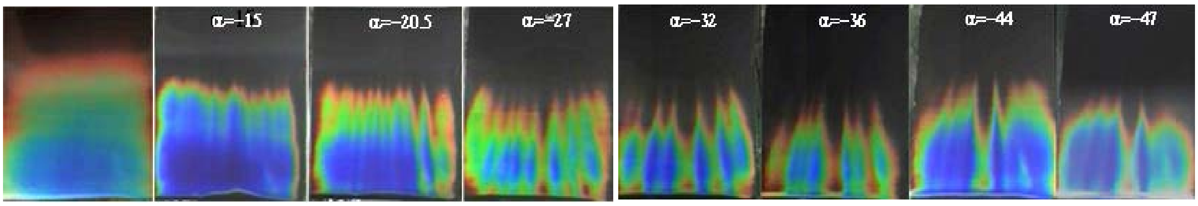
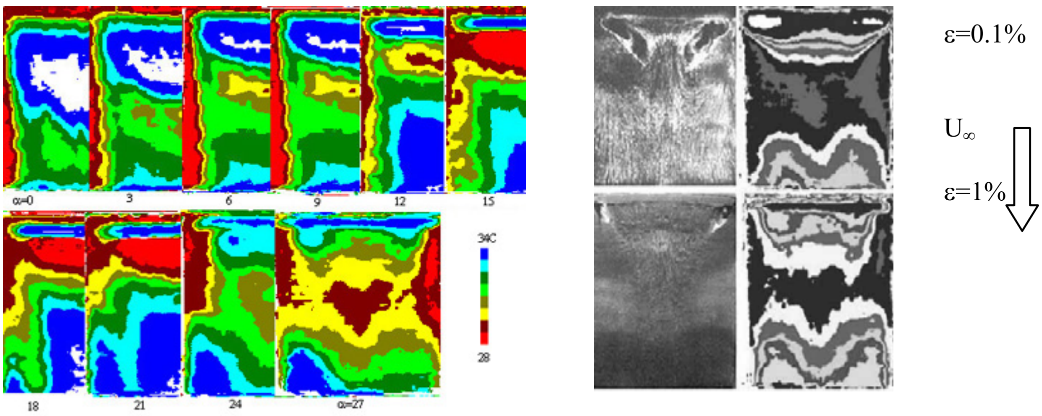


Figure 2. LC visualization of the flow pattern over the windward side of the wing. Re = $1.76 \cdot 10^5$. ε = 1%

Here, the baffling grid changed the flow characteristics, and the wing served as an indicator both for the characteristics themselves and for the effect due to the changed characteristics. Varying the distance from the grid and the angle of attack, we were able to observe real-time evolution of the near-wall flow. Without the grid (at ε=0.1%), on the model installed at zero incidence, the longitudinal structures were not observed since either the thermal effect due to these structure was weak or no such structures were present at all in the flow. With the grid, the longitudinal structures were first observed at an angle of attack close to the critical angle of about 18°; as the angle was increased, the transverse scale of the vortex structures also increased. Hot-wire measurements revealed the same spatial parameters of the longitudinal structures as the LC visualization.

Another actual problem aimed at the development of new flow control methods is the study of the 3D vortex structure of separated flows and examination of the influence of free-stream flow quantities on this structure. Figure 3a shows the distributions of temperature deduced from LC data for various angles of attack ranging from small to supercritical values for the lee side of the wing at $Re_c = 1.76 \cdot 10^5$ and an enhanced turbulence level ε=1% [27].



a) b)

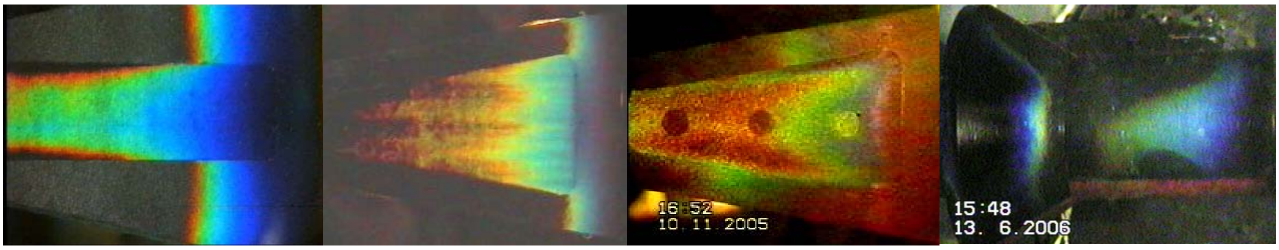
Figure 3. Temperature maps for the lee side of the wing (a) and comparison with oil-film visualization (b).

In this case, LCs visualize the thermal effects due to edge and tip eddies, and also effects due to a varied longitudinal pressure gradient. At large angles of attack, a laminar separation bubble and vortex foci are distinctly observed in the flow separation region. Figure 3b compares LC and oil-film visualization data at α=27°and turbulence levels of 0.1 and 1%.

Longitudinal structures originating in shear flows play an important role in the laminar-turbulent transition. LC coatings gave new information in this case too. In visualization tests performed in the T-324 low-turbulence wind-tunnel facility (free-stream turbulence level ε<0.04%), we examined the near-wall flow on the model of the same symmetric airfoil [29]. The studies were carried out both in an undisturbed free flow and in a flow with acoustically excited perturbations ($Re=1.5\cdot10^5$) on the model installed at two angles of attack, α=5.6° and 18°. The perturbations were produced by an upstream loudspeaker fed with a sinusoidal signal of certain amplitude and frequency. LC visualization showed that, in the case of α=5.6°, a separation bubble was formed in the flow, extended along the chord over a distance of 50 mm. Simultaneously, in the regions referring, according to the perturbation growth curves, to the final stage of the laminar-turbulent transition and to the turbulent boundary layer on the surface, there developed a system of longitudinal structures. These structures emerged as quasi-stationary (with fixed spatial position during the experiment) alternating bands with increased and decreased temperatures. On superimposing sinusoidal acoustic perturbations with a frequency inside the instability range, the position and the spanwise scale of the longitudinal structures underwent changes in comparison with the case of an undisturbed flow. With the perturbation frequency set to a value over the upper limit of the instability range, the picture was found to be coincident with that observed in the case of an undisturbed flow. In particular, the authors pointed out that, according to LC visualization and measurement data, the lateral wavelength of the longitudinal structures in the flow re-attachment region was roughly equal to the wavelength of the excited instability wave. At the larger angle of attack, α=18°, unlike the case with α=5.6°, visualization of the flow without acoustic perturbations revealed no longitudinal structures and, on the whole, the tests with superimposed acoustic perturbations yielded roughly the same results with some minor differences. It is shown that a gradual increase in the perturbation amplitude gives rise to longitudinal structures in the separated flow, resulting in elimination of the separation at sufficiently intense perturbations.

3.2. Visualization of thermal effects of different disturbances in hypersonic flows

Apart from fundamental studies, visualization performed by means of LC thermography can be used to solve many practical tasks. To improve the reliability of experimental data, careful test arrangement is required. LC visualization may be a very effective tool for this aim. For instance, it can be used to choose a proper position of discrete probes in the flow, to monitor the experimental procedure, e.g., the state and spatial position of the model, presence of defects on its surface, accuracy in assembling component parts, heat leaks, etc. These factors are hard to reveal with discrete probes. Below, several preliminary visualization pictures are presented to illustrate the afore-said [30,31]. Figure 4a shows an LC visualization of the temperature field on a metal flat-plate model with a rectangular insert made of a heat-insulating material. The plate was heated in a hypersonic flow with a Mach number $M_\infty = 6$. If the experiment duration was too long, the picture was found to become two-dimensional because of tangential heat spreading. Figure 4b shows the temperature field on a thermally insulated trapezoidal insert disturbed with longitudinal vortices induced by an upstream surface micro-roughness. In Figure 4c, the flow three-dimensionality indicates the quality of the model arrangement. Finally, Fig. 4d shows the temperature field on a cone-flare model visualized at $M_\infty= 21$. In particular, the installation angle of the model is seen to be non-zero here.



a) б) c) d)

Figure 4. LC visualization of tangential heat spreading (a), roughness-induced vortices (b), drawbacks in model arrangement (c) and asymmetry of flow pattern due to nonzero angle of attack (d).

4. Use of LC thermo-indicators in heat flux measurements

Traditionally, in measurements of heat fluxes, the researchers use either the steady-state or the 1D transient methods under various boundary conditions[9]. In the presence of tangential heat fluxes, corrections have to be introduced or 2D models for transient heat conductivity have to be applied.

Constant-heat-flux method. By way of practical example, we consider measurement of heat-transfer coefficients on the surface of a compact heat exchanger[32]. The surface under study is formed by two identical corrugated plates installed at an angle (θ) to each other (see Fig. 5) and uniformly heated with a known heat flux. Such channels are encountered in various heat-exchanging apparatus. An adequate choice of the heat-transfer intensification strategy (or, in fact, a proper choice of the geometry of the heat-exchanging surface) necessitates a detailed study of the flow pattern under different flow conditions. This flow pattern can be judged from the surface temperature and shear stress distributions revealed with the help of LCs. LC thermography allowed us to determine the generalized coefficients of steady heat transfer (local and integral Nusselt numbers) in a wide range of geometric parameters and flow conditions and to analyze the influence of θ on heat transfer. The experimental data gained were then used to obtain empirical dependences of the Nusselt number to the Prandtl number relations versus the Reynolds number $Nu/Pr^{0.4}=aRe^{b}$. The pattern of the surface shear stress distribution inside the channel (Fig. 5a) provided understanding of the heat-transfer intensification strategy

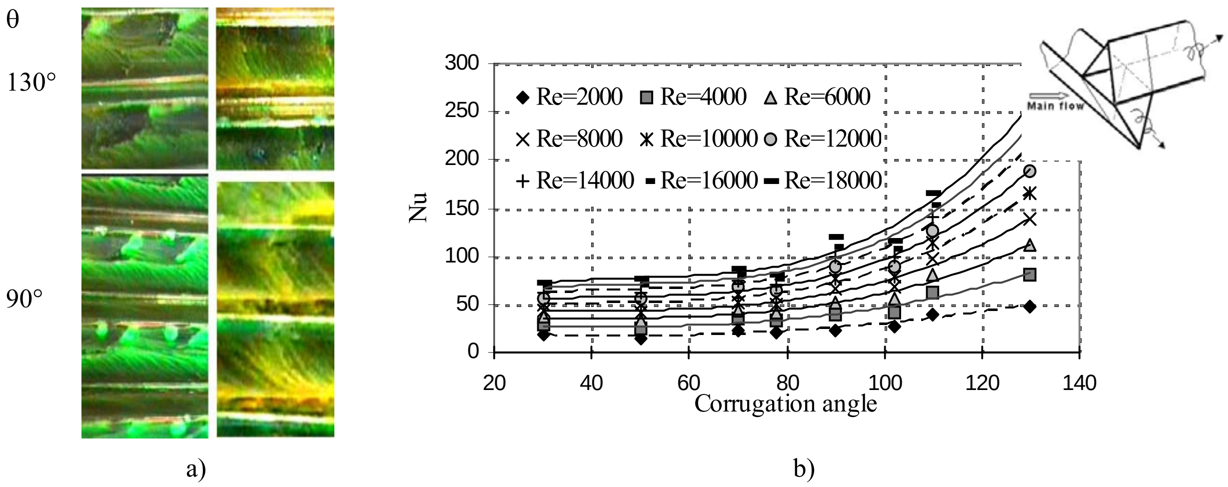


Figure 5. Fragments of the shear stress distribution on the lee (left column) and windward (right column) surfaces (a) and empirical Nusselt number versus corrugation angle at different Re numbers based on the hydraulic diameter (b).

Transient method. The LC coatings developed were tested[30, 31, 34] under conditions of long-duration hypersonic facilities of ITAM (AT-326 and T-327). The aim of these experiments was to study the possibilities of the LC technique for visualization and heat-flux measurements. The use of the transient method in tests with high heating rates imposes certain requirements on LC thermal indicators. To reduce the time required for performing the experiment, the LC working temperature range must be close to surface temperatures. It was shown that wideband LC coating should be used for panoramic visualization. As to quantitative heat flux measurements, narrow-band LCs provided higher accuracy. A comparative analysis of results obtained by three measurement techniques and numerical estimations was performed [30, 31, 34]. In particular, a comparison between experimental heat-flux rate data obtained by LC thermometry with data obtained by Atomic Layer Thermo Piles (ALTP) was made. In Fig. 6, the comparative data are shown for regimes with a total pressure Po=10 bar and total temperature between 243÷251C. It is seen that the data discrepancy is about 10%. The measurement uncertainties of the thermal indicator method were discussed in papers [30, 32].

Summary

The possibilities provided by liquid crystal thermography in qualitative and quantitative diagnostics of near-wall flows in a broad range of flow velocities are briefly considered in the paper. Several application examples are presented. The developed LC materials, advanced experimental procedures, and digital post-processing of video-frames permit both full-field visualization and measurement of surface temperature fields. A comparison of data obtained by means of LC thermography with data obtained with the help of traditional point probes prove the method of LC thermography to be highly efficient and capable of providing high accuracy in aerodynamic studies. The stationary method with LC coatings provides a relatively low uncertainty of absolute results, which are useful for comparisons with computational results. Application of low-temperature LCs and the transient technique made it possible to study aerodynamic heating in facilities with a high level of heat fluxes.

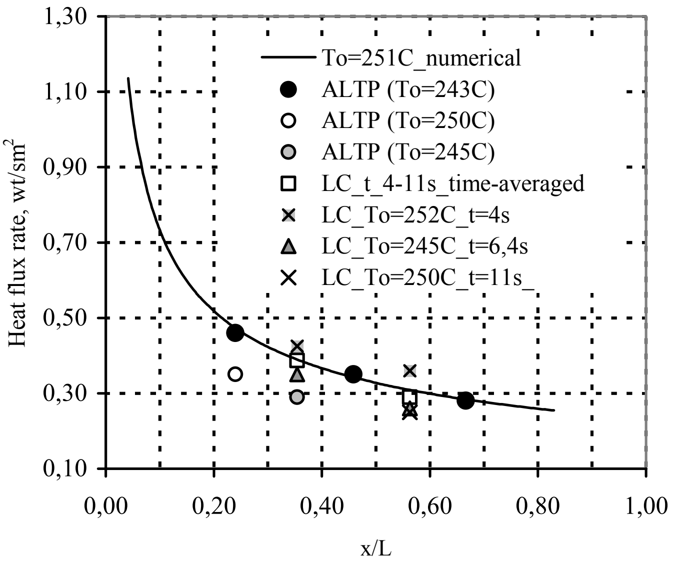


Figure 6. Heat flux rate measurements by three techniques for the plate model at M=6, Po=10 bar.

Acknowledgements

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