# 7. Temperature and Heat Flux

Thermochromic liquid crystals (TLCs) can be applied for thermographic measurements of heat transfer and temperature in fluid mechanics, delivering important quantitative full-field data for comparison with and validation of numerical simulations. Thin coatings of TLCs at surfaces are utilized to obtain detailed heat transfer data for steady or transient processes. Application of TLC tracers allows instantaneous measurement of the temperature and velocity fields for two-dimensional cross sections of flows. These methods are based on computerized true-color analysis of digital images for temperature measurements and modified particle image velocimetry, which is used to obtain the flow field velocity. In this Chapter, the advantages and limitations of liquid-crystal thermography are discussed, followed by several examples of thermal flow field measurements.

The use of infrared thermography for non-intrusive measurement of spatially resolved surface heat transfer characteristics is described for five different measurement environments, including situations where large gradients of surface temperature are present. In the first of these, measurements are made on the surface of a therapeutic biomedical patch, where the quantity of interest is the time-varying spatially resolved surface temperature. For the other situations, the measured temperature distributions are used to deduce quantities such as the surface Nusselt numbers on the surface of a swirl chamber, the effectiveness of surface adiabatic film cooling downstream of individual shaped film cooling holes, the surface heat flux reduction ratio downstream of two rows of film cooling holes placed on a model of the leading edge of an airfoil, and thermal boundary condition information for numerical predictions of the heat transfer characteristics on the surface of a passage with an array of rib turbulators. In all of these situations, in situ calibration procedures are employed in which the camera,

imaging, and data-acquisition systems are all calibrated together in place within the experimental facility as the infrared measurements are obtained. This requires separate, simultaneous, and independent measurements of surface temperatures, and produces spatially resolved results from infrared images with high levels of accuracy and resolution.

**Part B | 7**

# 7.1 Thermochromic Liquid Crystals

The description of transient temperature fields is one of the most sought after goals of experimental fluid mechanics. Unfortunately, performing accurate temperature measurements is not an easy task. Point measurements, which are the most common, usually give insufficient information if complex configurations are investigated. Full-field measurements, although not as accurate, may offer greater confidence for comparison with the numerical results. One such full-field technique is based on the use of *thermochromic liquid crystals* (TLCs). Their use to study heat transfer, flow visualization, and thermal mapping is playing an increasing role in the compilation of experimental temperature-related data in several areas of applications, competing with or replacing traditional infrared thermography [7.1].

Liquid crystals are highly anisotropic fluids that exist between the phase boundaries of the solid phase and the conventional, isotropic liquid phase [7.2]. Their temperature sensitivity is based on the property of some cholesteric, chiral-nematic liquid-crystal materials. This phase is typically composed of molecules arranged in a stack of very thin layers with the director in each layer twisted with respect to those above and below. An important characteristic of the cholesteric mesophase is the pitch, which is defined as the distance over which the director rotates a full turn in the helix structure of the nematic layers. The helical structure of the liquid-crystal material is responsible for its ability to selectively reflect light of wavelengths related to the pitch length. As the incident light passes through a TLC material, the periodic variation of the refractive index (Sect. 6.1) modulates the light polarization and causes interference within the multilayered material. According to Bragg's law, a characteristic light wavelength is singled out depending on the light scattering angle, refractive index and structure periodicity. Hence, a single color will be reflected when the molecular pitch is equal to the corresponding wavelength

of light in the visible spectrum. Temperature variation or stress executed on the sample will change the director orientation in successive molecular layers, which modifies the pitch length. This makes it possible to use liquid crystals as temperature indicators, where detection of the color change in reflected light leads to quantitative information. The side effect, stress sensitivity of the liquid crystals, is successfully used in fluid mechanics to detect shear or pressure changes [7.3]. However, for temperature measurements this should be minimized to avoid ambiguity of information given by color changes.

Bulk TLC material is normally clear, or slightly milky in appearance. It shows a change of color to red in response to an increase of temperature, followed by yellow, green, blue, violet, finally turning colorless again at higher temperatures. The molecular transition responsible for the selective light reflection is limited to a narrow range of temperature variation, defined for a specific TLC material as the *color play range*. The color changes of TLCs are repeatable and reversible as long as the material is not physically or chemically damaged. This being the case, TLCs can be calibrated accurately with proper care and used as temperature indicators. They modify incident white light and display color with a wavelength that is related to temperature. Beyond its *clearing point temperature*, a TLC material is a transparent liquid, simplifying its use as an additive to paints, filters or warning labels.

Pure liquid-crystal materials are thick, viscous liquids, and are greasy and difficult to deal with under most heat transfer laboratory conditions. TLC materials are also sensitive to mechanical stress. A microencapsulation process that encloses small portions of liquid-crystal material in polymeric material has been introduced to solve problems with stress sensitivity and chemical deterioration.

In the past liquid crystals have been extensively applied in the visualization of entire, either steady-state

or transient temperature fields on solid surfaces. Since quantifying color is a difficult and somewhat ambiguous task, application of TLCs was initially largely qualitative; application of color photography or interference filters for color analysis was tedious and inaccurate. Quantitative and fast temperature measurements were only brought about with the adoption of the charge-coupled device (CCD) color camera and digital image processing. The rapid development of hardware and software image-processing techniques has made the use of inexpensive systems, real-time, transient, full-field temperature measurements using TLCs possible.

Thermochromic liquid crystals can be painted onto a surface [7.4–11] or suspended in the fluid to render the temperature distribution visible [7.12–16]. By disseminating the liquid-crystal material throughout the flow, TLCs not only become classical tracers for flow visualization, but simultaneously, minute thermometers monitoring the local fluid temperature (Fig. 7.1).

The typical diameter of TLC tracers used in flow measurements is 20–50 µm. As the density of TLCs is close to that of water, they are well conveyed in liquid flows. The response time of TLC materials is 3–10 ms, sufficiently fast for typical thermal problems in fluids. Application of TLCs as tracers facilitates instantaneous measurement of temperature and velocity fields [particle image velocimetry (PIV); Sect. 5.3.2] in a two-dimensional cross section of the flow. It is a unique method of combining full-field temperature and velocity measurements [7.17–20]. In the following we give some details on application of TLCs for fluid mechanics meas-

urements, mostly gained through our own experience *playing with colors* during the last 20 years.

## 7.1.1 Materials

Generally there are three different forms of TLCs available: unsealed pure cholesteric material, slurries of encapsulated TLCs, and mechanically protected thin liquid-crystal films. TLCs can be purchased in one of these forms with the chemical composition matched to the temperature variation of the problem. Typically they have a color play range of about 0.5–40 °C, associated with clearing point temperatures of −30 °C to above 120 °C. The proper choice of material depends on the application. Its working temperature (clearing point) should match the expected temperature range. Selection of narrow-band TLCs offers accurate resolution of temperature but only over a very narrow interval. This is convenient in detecting transient changes of temperature, where the passage of a single, well-defined isotherm through the investigated media can easily be detected. Broadband TLCs give rather qualitative information, discriminating hot and cold regions with very little accuracy of measured temperature values. It is worth noting that most TLC producers define the temperature response of their products using a null angle between illumination and observation. These must be modified according to Bragg's law for other configurations, which results in a shift of the clearing point and shrinkage of the bandwidth of the TLC's color response. Table 7.1 shows the basic properties of a few TLC sam-



**Fig. 7.1a−c** Natural convection in a differentially heated box. Three different flow regimes are visualized using unencapsulated liquid-crystal tracers: **(a)** Low Rayleigh number ($10^4$): temperature difference between walls 4 °C, TLC material TM107, box size 38 mm; **(b)** Intermediate Rayleigh number ($8 \times 10^4$): temperature difference 16 °C, TLC material TM445, box size 38 mm; **(c)** High Rayleigh number ($1.3 \times 10^8$): temperature difference 34 °C, TLC material TM317, box size 80 mm. Images **(a)** and **(b)** were obtained from color slides exposed 20 times every 15 s; image **(c)** was created from 20 digital images taken every 200 ms and added in a computer memory

**Table 7.1** Thermochromic liquid crystals applied to flow measurements. Nominal red clearing point $T_{\text{start}}$ and temperature range $\Delta T$ according to catalogue data

| Company | Symbol | $T_{\text{start}}$ (°C) | $\Delta T$ (°C) | Form | Comments |
|---|---|---|---|---|---|
| Hallcrest | BM 250/R0C 10W /S33 | 0 | 10 | Encapsulated | $\Delta T \approx 5\,°C$, heavy tracers |
| Hallcrest | BM 100/R90F 2W /S33 | 32.5 | 2 | Encapsulated | |
| Hallcrest | BM 100/R90F10W /S33 | 32.5 | 10 | Encapsulated | |
| Hallcrest | BM R29C 4W /S33 | 29 | 4 | Encapsulated | |
| Hallcrest | BM 100/R20C10W /S33 | 20 | 10 | Encapsulated | |
| Hallcrest | BM 100/R6C12W /S33 | 6 | 12 | Encapsulated | |
| Hallcrest | BM 100/R29C4W /S33 | 29 | 4 | Encapsulated | |
| Hallcrest | BM /R96C6W | 96 | 6 | Liquid | |
| Hallcrest | BM /R60C6W | 59.8 | 6 | Encapsulated | |
| Hallcrest | BN /R70C6W | 69.5 | 6 | Liquid | |
| BDH | TM 445 (R17 C6W) | 17 | 6 | Liquid | Strong colors, $\Delta T \approx 4\,°C$ |
| BDH | TM 446 (R37 C6W) | 37 | 6 | Liquid | Strong colors, $\Delta T \approx 4\,°C$ |
| BDH | TM 317 | 21 | 20 | Liquid | Strong colors, $\Delta T \approx 4\,°C$ |
| BDH | TM 107 (R27 C6W) | 27 | 8 | Liquid | Strong colors, $\Delta T \approx 3\,°C$ |
| Merck | TM 912 | −2 | 10 | Liquid | Strong colors |
| Merck | TCC 1001 (27C-31C) | 27 | 4 | Encapsulated | Very stable suspension |

ples used as tracers with some practical remarks about their usage.

Liquid-crystal organic compounds degrade very easily when exposed to chemical contamination and to ultraviolet light. Slight chemical contamination may shift the color play range over several degrees Celsius or even completely remove the TLC temperature sensitivity. In our experience, apparently negligible sources of contamination such as the use of polyvinyl tubes for providing the suspension of liquid crystals appear to produce surprisingly strong effects on the TLC response characteristics. As the effect of chemical deterioration is usually difficult to predict, it is recommended to use unsealed TLCs only in water and its solutions with glycerol. For all other flow configurations protection through encapsulation is necessary. Despite this inconvenience in most of our experiments pure, unsealed TLCs material was used to produce TLC tracers. There are two main reasons for this. Pure material offers a very good signal-to-noise ratio for color evaluation. For large enough tracers and for glycerol or water as a carrier liquid, the intensity of light scattered by unsealed TLCs (Mie scattering band) beyond their clearing point is negligibly small. Hence, tracers are practically invisible for temperatures outside their color play range. This practically cancels any secondary light scattering, improves color evaluation, and allows for deeper optical penetration in the flow. The second reason for using pure TLCs material, which is very important in our experi-

ence, is their flexibility in matching the color play range. In experiments where phase changes takes place (freezing, boiling) the color play of TLCs must exactly match the desired temperature range. Usually it is not possible or very expensive to obtain TLCs manufactured exactly to that range, and even then experimental conditions may shift the resulting color response, making new, expensive matching of the ordered TLCs necessary. The same result can be achieved simply in the laboratory using unsealed material by mixing two samples of TLCs with clearing points above and below the desired working temperature. The mixture obtained will exhibit temperature sensitivity in the range proportional to its composition.

Pure TLC material is commercially available as a thick, viscous liquid. It can be dissolved in several organic solvents (e.g., diethylether) and sprayed onto the solid surface or directly into the fluid to be investigated. It is also possible to emulsify them into the liquid by strong mixing with the carrier fluid. When applying unsealed TLCs as tracers, it is important to achieve a homogeneous, very dilute suspension of small droplets. The size of the tracers should be minimized to avoid buoyancy effects and guarantee that tracers follow the flow pattern. However, they should be large enough to be detectable and, what is even more important in the case of TLCs thermography, to guarantee a strong enough signal-to-noise ratio of reflected light for color evaluation.

Several techniques have been investigated to achieve this target. Mixing diethylether solutions of TLCs with a hot carrier liquid is a relatively simple and efficient method. First, a thin layer of the solution is left at the liquid surface until the ether has completely evaporated. Then, by mechanical stirring, a tiny microlayer of pure TLC is broken into a suspension of microdroplets. However, the resulting droplets vary quite substantially in size and an additional selection procedure (sedimentation) is necessary to remove the large ones. The method was improved using piezoceramic droplet generator to disperse the ether TLC solution in a 2 m-high fall tower [7.21]. The ether solvent in droplets with a diameter of 0.4 mm completely evaporates during their flight, and pure TLC material can be collected in the carrier liquid. The apparatus allows a suspension of almost perfectly monodisperse TLC droplets with a diameter of 50 μm to be obtained, evidently improving the quality of tracer images (Fig. 7.1a,b). A less tedious but in most cases satisfactory method of dispersing pure TLC materials in liquids is turbulent mixing of a preheated carrier liquid doped with a small amount of hot TLC material. Using this method, the TLC droplet size is 10−50 μm, forming a uniform colorful mist when observed by a CCD camera.

Perhaps the most common method employed for flow visualization experiments is the application of encapsulated TLCs, which are commercially available as slurries of polymer capsules in water. Each microcapsule, of size 50−150 μm, contains approximately 40% (by weight) of enclosed TLC material. These are custom formulated for the required color change properties. It is possible to control the buoyancy (apparent specific gravity) characteristics of the microcapsules within limits by varying the composition of the TLC mixture, and the microcapsule diameter and wall properties. The TLC slurry can be added directly to the carrier fluid. Theoretically, it should be possible to use such microcapsules in any liquid that is not aggressive to the encapsulation material. Since the slurry carrier is water, in practice it seems that they can only be mixed with aqueous solutions of glycerol, ethylene glycol, and other similar low-molecular-weight polyhydric alcohols. Seeding with dry particles is not possible. Polymeric shells enclosing TLC materials are very fragile. Any attempt to remove the TLC particles from the slurry by drying or filtering leads to their damage and loss of their content. Perhaps the only nonaqueous carrier liquid successfully used with encapsulated TLCs is silicon oil. Usually encapsulated TLCs produce less-saturated colors. Light diffused by the capsule creates an additional white background in addition to the selective reflection by the liquid crystals, decreasing the saturation of the analyzed colors and the overall transparency of the carrier liquid. Therefore the potential advantages of using encapsulated TLCs, the chemical and mechanical protection of the TLC material, is diminished by the reduced flexibility in matching size and composition, their worse optical properties, and the much higher unit price.

For surface temperature measurements, the unencapsulated material (unsealed liquid) is applied to a clear plastic sheet and sealed with a black backing coat to form a prepackaged assembly. Commercially temperature-indicating devices using a thin film of liquid crystal sandwiched between a transparent polyester sheet and a black absorbing background are available. If chemical or mechanical protection is not a serious problem, it is possible to deposit pure material directly onto the black surface. Evaporation of an ether solution of TLCs has been successfully used to cover interrogated surfaces with a very uniform, thin microlayer of thermochromic material.

Application of TLCs sheets and films is limited to measurements of the heat transfer coefficient and temperature distribution over areas that are difficult to access with other complementary techniques such as infrared (IR) thermography. TLC films have an advantage over IR techniques in all configurations where direct monitoring of long-wavelength infrared radiation is obstructed, for example by a water film falling over the surface in question. However, obtaining quantitative measurements with TLC films is not simple and in many cases impossible due to artefacts produced by nonuniform illumination of the interrogated object. Additional sources of uncertainty are heat flux resistance occurring between the surface and the thermochromic foil or unknown variations of the effective thickness of the thermosensitive paints sprayed over the surface.

## 7.1.2 Illumination

TLCs show colors by selectively reflecting incident white light. The observed color depends on the TLC temperature and also on the reflection angle, measured relative to the incident light direction. The effects are different in thin films and paints compared to tracers suspended in liquids. In both cases two basic rules apply:

1. the light source should have smooth and stable spectral characteristics, and

2. the angle between the observer (camera) and the direction of incident light should be kept fixed across the whole monitored area.

To fulfil the first condition, collimated light from strong halogen lamps or xenon flash tubes is practically the only choice. For flow illumination, strong and relatively easily fabricated light sources are assembled using linear 1000 W halogen lamps with a tungsten filament spanning a 150 mm tube. Lamps are switched on for only a short time (0.5–5 s) to avoid excessive heating and to extend the lifetime of the filaments. A filament preheating circuit is used to speed up switching of the lamp to full power. High-energy xenon discharge lamps are employed for short illumination times. Such lamps consist of a 150 mm-long tube connected to a battery of condensers and can deliver as much as 1 kJ of energy during a 1 ms pulse. Repetition of the light pulses is relatively slow (several seconds). The total thermal load and condenser charging time are both factors limiting the repetition rate. In practice, two sets of condensers with an electronic switch can be used to allow two light pulses to be emitted from the same tube within approximately 200 ms. Such a configuration is useful when applying TLC tracers for simultaneous temperature and velocity measurements (particle image thermometry (PIT) and velocimetry (PIV); for the latter see Sect. 5.3.2).
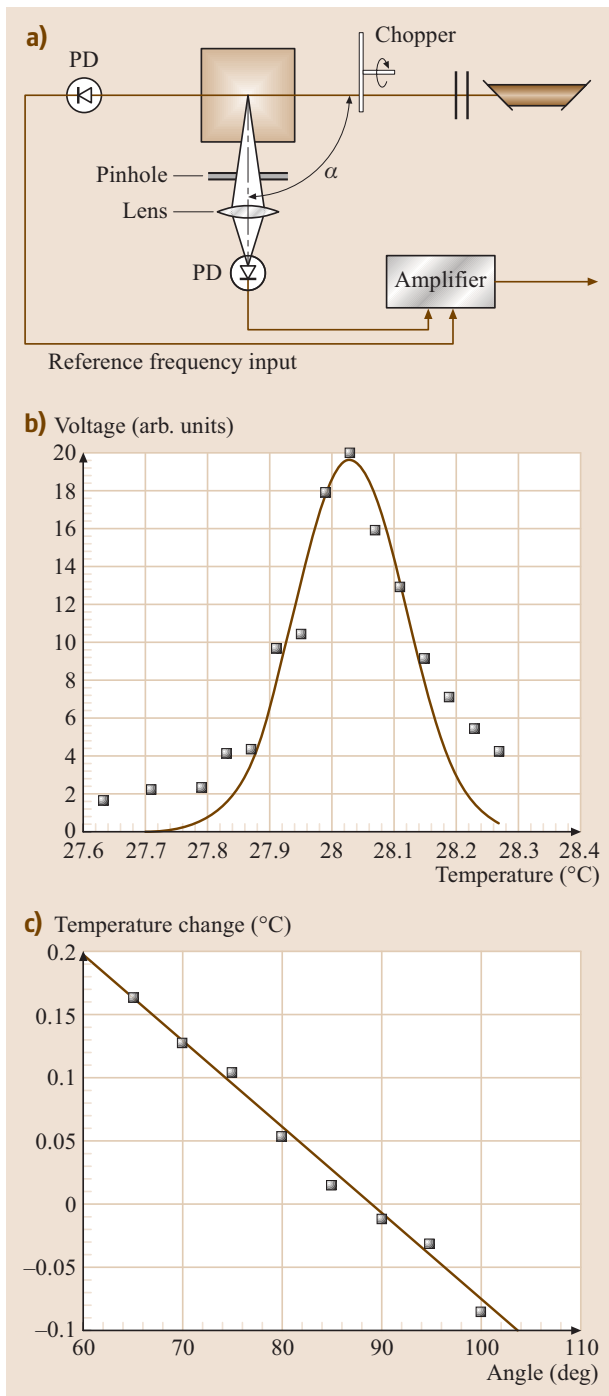
For surface temperature measurements special care is necessary to avoid specular light reflections form the surface covered by the TLCs. Sometimes polarization filters may help to minimize this effect. Application of diffuse light, often preferred for the illumination of complex surface geometries, introduces uncertainty in the color–temperature relation and limits the accuracy of measurements due to variation of the illumination/observation angle over the investigated area. To avoid additional heating by irradiating light, infrared filters and short light pulses should be applied. Use of fluorescent tubes is not advised as the illumination they produce is pulsating in time and spectrally discontinuous.

Incident light should be collimated to achieve well-defined conditions for Bragg reflection of a single wavelength. This is especially important for tracers, where reflected light is observed directly. For TLCs sealed between multilayered films, internal light reflections partially diminish their sensitivity to the observation angle variation. In some surface temperature studies, variation of the lighting/viewing angle by up to 30° is often accepted as a compromise between il-

lumination uniformity and good color resolution [7.4]. However, for quantitative measurements such a compromise is not acceptable and, as pointed out by *Sabatino* et al. [7.10], only a calibration over the full viewing area can help to remove viewing angle bias from surface temperature measurements. In practice this requires a calibration curve for each point (image pixel) of the analyzed surface. Such a technique, which is easy to perform when using digital recording, takes into account most sources of uncertainty in the perceived hue, including reflections, nonuniformity of the color response characteristics of the CCD pixels, lenses, and optical windows.

Good collimation of panchromatic (white) light, which is necessary for quantitative temperature measurements, is not an easy task. Optical passages including multiple slits, parabolic mirror and cylindrical lenses are used to extract a 2 mm-thick 100 mm-wide sheet of light from a halogen or flash tube, with the sheet collimation preserved over a distance of about 10 cm. The cost of this is strong attenuation of the light intensity, leaving little left from a 1000 W light source. To resolve the difficulties of light collimation it is possible to apply a bundle of three monochromatic light sources, such as lasers or laser diodes operating at blue, green and red colors. However, an additional problem arises with equalizing the color balance at every illuminated point. Hence, in practice lasers (HeNe) are applied for the illumination of TLCs only to extract single isotherms for calibration purposes.

A procedure has been developed to resolve the question of the single-wavelength accuracy of the method and its sensitivity to variations in lighting and viewing angle [7.22]. A suspension of unsealed TLCs (TM317) in glycerol was produced using the aforementioned ether-solvent-based dispersing method. Calibration of the suspension was performed in a small cubic container (38 mm internal size) made of Plexiglas, with top and bottom walls made of black, oxidized metal. Both metal walls were kept at a constant temperatures, 28.7 °C for the top and 26.6 °C for the bottom, ensuring stably stratified thermal field in the liquid. The temperature in the cavity varied linearly with height, with small deviations in the vicinity of the Plexiglas side walls. The liquid was illuminated by a chopped 0.5 mm-diameter laser beam from a 5 mW HeNe laser, passing through the center cross section of the cavity (Fig. 7.2a). The scattered light was observed in the perpendicular direction ($\phi = 90°$) with an optical system equipped with a focusing lens and a photodiode. Scattered light was collected from a region approximately 1 mm in size, selected in the middle

**a)**



**b)** Voltage (arb. units)



**c)** Temperature change (°C)



**Fig. 7.2a−c** Intensity of HeNe laser light scattered by suspension of unencapsulated TLC tracers (TM317) kept in a stable vertical temperature gradient in a 38 mm Plexiglas box: **(a)** schematic of the apparatus, **(b)** effect of temperature variation, **(c)** effect of the angle of observation on the measured temperature shift

red-band sensitivity of TLCs. A strong peak in the signal was observed (Fig. 7.2b) when the condition for matching the laser wavelength with the TLCs characteristic pitch was reached. The near-Gaussian shape of the signal, with a half-amplitude width corresponding to a 0.2 °C temperature change, indicates the nominal sensitivity of the TLC sample. This value corresponds to the ideal conditions of 633 nm-wavelength evaluation of isotherms, and for the given experimental configuration defines the minimum error of quantitative temperature measurements in the red part of the color play range of the TLC sample. The dependence of the reflecting angle on the temperature shift was evaluated by varying the position of the detector on the arc centered at the interrogated point of liquid. Figure 7.2c illustrates the linear decrease of the detected light intensity, with a slope corresponding to a change of 0.07 °C in the recorded temperature for each 10° change in the viewing angle. This test underlines the importance of preserving a fixed angle between the illuminated plane (light sheet plane) and the camera, and keeping the viewing angle of the lens small. For example, observing a 5 cm-wide area with a CCD camera in the perpendicular direction, the observation distance should be about 400 mm to keep the viewing angle below 4°.

## 7.1.3 Acquisition and Calibration

The calibration procedure is the most tedious and delicate element of TLCs thermography. Due to the unstable properties of TLCs and the large sensitivity of their color response to experimental conditions, the same illumination and recording system should be used for calibration and measurements. This guarantees that color bias due to external optical effects is taken into account. A typical experimental setup used for quantitative thermography consists of an illumination set, a three-chip CCD color camera and a 24 bit frame grabber. A commercially available standard three-CCD camera can be used, but its color response should be verified and properly balanced. The electronically generated color bars are useful to balance the gain and contrast of each of three color channels. Features that compensate for the nonlinear color response of the human eye, automatic gain, and white

of the beam. The scattered light intensity was monitored using a differential, phase-locked voltmeter. Moving the cell up and down with a micrometer screw, liquid layers with linearly varying temperature were interrogated. The intensity of the scattered light (reflected by the TLCs) remained almost constant until the temperature-matched

Part B | 7.1

balance, usually set by default in standard cameras, should be deactivated.

For flow measurements, the investigated cavity is illuminated with a thin sheet of white light from the aforementioned halogen lamp or xenon flash tube and observed in the perpendicular direction. The color images, typically of $768 \times 564$ pixels, can be easily acquired using a color frame grabber installed in a personal computer equipped with a peripheral component interconnect (PCI) or Firewire (IEEE 1394) interface. The setup (Fig. 7.3) additionally consists of a computer-controlled system of three stepper motors, which allow the automated acquisition of several horizontal and vertical planes across the flow within one or two minutes. Hence, for slowly varying flow structures, a transient recording of three-dimensional flow features is possible. Recording of the transient flow patterns and temperature fields is performed periodically. Typically every $10–300$ s, a short series of images is acquired and stored on the hard disk of the computer for later evaluation. In the case of TLC tracers their displacement can be analyzed using the PIV technique (Sect. 5.3.2, and full flow velocity fields are obtained [7.18].

Temperature measurements using TLCs are based on color analysis of the images and needs appropriate calibration. This is eased by using preprocessed color information from a three-CCD camera, which splits light into three basic components: red, green and blue (RGB). This process is known as trichromic decomposition. Each of the three color components is usually recorded as a separate 8 bit intensity image. Numerous methods of subtracting color information from a trichromic RGB signal exist [7.6]. The most straightforward is to convert the RGB trichromic decomposition to another trichromic decomposition based on *hue* (color value), *saturation*, and *intensity* (HSI). Such a decom-

position is common in image analysis and also serves as a natural means of converting color images to their black-and-white representation. Classical conversion of an RGB color space to an HSI decomposition is based on three simple relations. Light intensity $I$ (or brightness) is defined as the sum of its three primary components:

$$I = \frac{\sqrt{(R^2 + G^2 + B^2)}}{\sqrt{3}} \tag{7.1}$$

with $R$, $G$ and $B$ being the intensities of the red, green and blue components, respectively.

Using an 8 bit representation, the maximum intensity is equal to 255. The saturation $S$ represents color purity, i. e., the relative value of the reminder after subtracting the amount of colorless (white) light:

$$S = 255 \left( 1 - \frac{\min(R, G, B)}{I} \right) . \tag{7.2}$$

In our representation pure colors have saturation equal to 255. The hue $H$ relates to the dominant color and is usually obtained from the algebraic or trigonometric relation between the two dominant primary colors. To make use of the 8 bit signal dynamics and limiting ourselves to the spectral colors [7.18], the following formula is used to calculate the hue value:

$$H = \begin{cases} 63 + [(G' - R')63]/(G' + R') & \text{for } B' = 0 , \\ 189 + [(B' - G')63]/(G' + B') & \text{for } R' = 0 , \end{cases} \tag{7.3}$$

where $R' = R - \min(R, G, B)$, $G' = G - \min(R, G, B)$, and $B' = B - \min(R, G, B)$.

Temperature is determined by relating hue to a temperature calibration function. This is the most critical stage of TLC-based thermography. Light refracted by TLCs is not monochromatic, even if the observed sample has a uniform temperature. Color depends on observation angle, the scattering properties of the TLCs material, the color and refractive index of the carrier liquid, and may also vary with the size of the particles. Additional factors, such as the color of the light source, the color transmission properties of the acquisition system, as well as reflected and ambient light modify the resulting color information. The observed color may also depend on light intensity. Very careful calibration is therefore necessary to obtain quantitative information. It is advised to generate a separate calibration curve for each small area of the investigated surface and use these to normalize the measured color information.

For the best effects the calibration procedure should be performed with an identical experimental arrangement to that used for measurements. To perform the
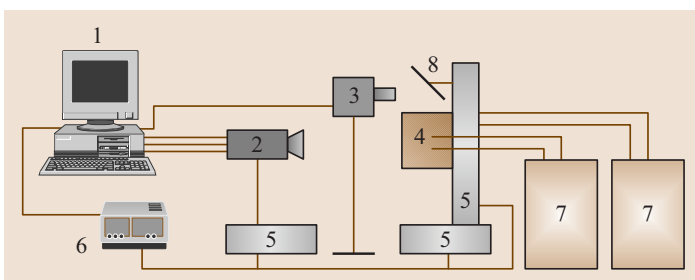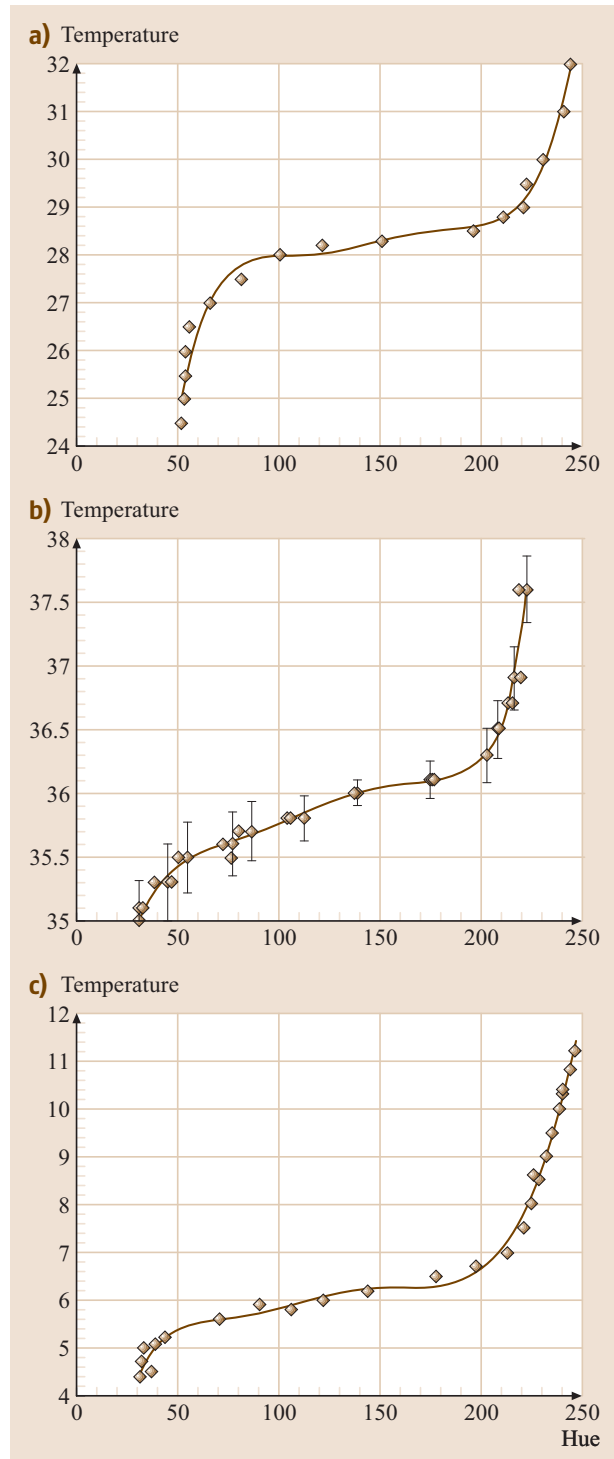


**Fig. 7.3** Schematic of the experimental system. PC (1) with the acquisition card controlling the color camera (2), halogen lamp (3) and three stepping motors (5) using a driver (6). The temperature in the cavity (4) is controlled by two thermostats (7); the mirror (8) used to direct the light sheet

calibration, an interrogated surface or liquid in a cavity with a suspension of TLC tracers must be kept at a constant and uniform temperature. Temperature stability and uniformity better than 0.1 °C is required for TLCs with narrow color bands. For measurements of temperature fields in liquids this is achieved by keeping the walls of the experimental cavity at a constant temperature and continuously mixing the liquid with a magnetic stirrer. Data for calibration are obtained by adjusting the liquid temperature in small increments (usually 0.3 °C steps) and acquiring several sequences of images for future processing. Compared to surface thermography, the use of TLCs suspension for flow investigations yields additional problems. The color images of the flow are discrete, i.e., they represent a noncontinuous cloud of points and their color usually varies from point to point. This is not only caused by slight variations in the TLC temperature responses but also indicates local fluctuations in the fluid temperature present due to the limited thermal diffusivity of liquids. To minimize this effect, calibration is usually performed for small areas of about $30 \times 30$ pixels, extracted in the vicinity of the temperature sensors from each image and averaged for several subsequent images.

Hue evaluation is performed for each pixel of the resulting averaged image, under constraints of minimum and maximum pixel intensity and minimum saturation. Only good pixels, i.e., those having an intensity and saturation above a given threshold level, are used to build a hue matrix, which is smoothed using a $5 \times 5$ median filter followed by a low-pass filter. An average hue value is then calculated for each image and used as a reference point for the calibration procedure. The procedure can be repeated for several parts of the image to create a position-dependent temperature–hue relation. For the full color range of TLCs about 20–30 calibration points are collected at gradually increasing liquid temperatures. A smooth and unique hue–temperature relation is established by fitting a polynomial of degree 6–10. After removing outliers, a final fit is performed to obtain a smooth temperature–hue function (Fig. 7.4). The accuracy of the measured temperature depends on

the color (hue) value as a direct consequence of the nonlinearity of the curve. The relative error is 3–10%, and is based on the temperature range defined by the TLC color play limits. It is estimated by calculating the uncertainty



**Fig. 7.4a–c** Temperature versus hue calibration points and high-order polynomial fits for three different TLCs dispersed as tracers in a flow. **(a)** Encapsulated tracers TCC1001 in water; **(b)** Suspension of unencapsulated TLCs TM446 in water, error bars indicate estimated accuracy; **(c)** Mixture of two TLC types (TM445 and TM912) used to produce a suspension of liquid crystals matching the desired temperature range

of single-point measurements from several images of the same flow. For the TLCs used to obtain the curve in Fig. 7.4b (TM446), an absolute accuracy of 0.15 °C results for low temperatures (red–green color range) and 0.5 °C for high temperatures (blue color range). The most sensitive color region is the transition from red to green, which occurs over a temperature change of less than 1 °C. Additional, quantitative information beyond the calibration curve can be obtained by careful analysis of the remaining two components of the color decomposition. These can be used to analyze the temperature in areas of the TLC clearing point, which exhibits a gradual fall in pixel intensity and the saturation of colors. Quantitative evaluation of these areas is difficult but possible, for example using neural networks to include complete image information in the color analysis [7.23].

Obtaining full calibration curves prior to each experimental run is not only tedious but also limits rapid repetition of different experimental configurations. Such repetitions are often necessary, for example when different TLCs are used to shift the analyzed temperature range. Observing the shape of different calibration curves taken under similar conditions we may find large similarities. Therefore in some cases it is possible to assume the existence of a general calibration curve, independent of the active range. A calibration procedure based on such a *master* curve would require only a few measurements to produce a useful calibration over an entire active range. Using a nondimensional representation of temperature *Hay* and *Hollingsworth* [7.6] obtained repeatability of their regression curves with an acceptable accuracy for TLCs painted onto a heated surface.

Similarities are also observed for the regression curves obtained for TLC tracers (Fig. 7.4). For reproducible experimental conditions simple stretch and shift operations may be used to transform one of them to another. Such a procedure can be applied to account for small changes of TLC response, either due to aging or when a new mixture is prepared.

### 7.1.4 Examples

In the following we illustrate several applications of TLC tracers to study the natural convection of liquids in closed cavities, and also with a phase change (freezing of water). In conjunction with the experimental program, numerical simulations of the problem were performed using finite-difference models of the Navier–Stokes and energy equations [7.13, 18, 24, 25]. The significance of the full-field temperature and flow measurements for the verification of the numerical results becomes evident by a direct comparison of the evaluated and predicted fields.

The first experiment deals with natural convection in a cubic cavity with two vertical, isothermal walls kept at different temperatures. This flow configuration resembles a popular benchmark, an idealized case of the flow in a cubical cavity used to test numerical solutions of the Navier–Stokes equations [7.26]. The characteristic recirculating flow is generated in the cavity by the temperature gradients between the two opposite metal walls of the cube. In addition to its theoretical interest, this type of convective flow has numerous potential applications, among which probably the most popular
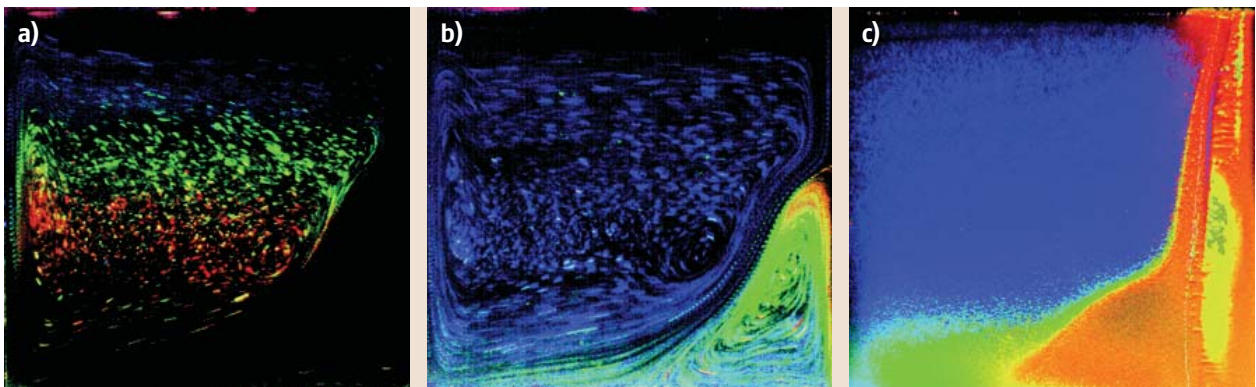


**Fig. 7.5a–c** Visualization of natural convection in water close to the freezing point, using a hot (left) wall at a temperature of 10 °C and a right wall at a temperature of 0 °C for **(a)** and **(b)**, −10 °C for **(c)**. Three types of liquid-crystal tracers were used to indicate the temperature variation: **(a)** encapsulated TLCs BM100/R6C12W showing details of flow and temperature for *normal* circulation (on the left); sum of 10 images taken every 1 s; **(b)** TLC mixture (TM445 and TM912) active at lower temperatures, visualizing the complex structure of *abnormal* circulation; sum of 20 images; **(c)** TLC mixture with a composition matched to the freezing point

is that of double glazing. Initially our interest was directed towards understanding the flow in the vertical central plane of the cavity. For this purpose, the observations of flow patterns and temperature fields were performed for several systems with increasing Rayleigh number [7.13, 14]. The flow structure in the differentially heated cavity strongly depends on the Rayleigh number. At small Rayleigh number ($\text{Ra} < 10^3$) the flow is dominated by conduction, which is seen in the form of vertical isotherms across the cavity. In the parameter range analyzed ($\text{Ra} = 2 \times 10^4 - 10^5$), both convection and conduction are important. At the lower end of the range, heat transfer due to convection begins to play a significant role, generating a vertical temperature gradient in the center of the cavity. The horizontal temperature gradient is positive everywhere. The streamlines correspond to a single roll located at the center of the cavity. This can be well observed in the multiply exposed photographs of liquid-crystal tracers conveyed by the flow of glycerol (Fig. 7.1a). At higher Rayleigh numbers ($\text{Ra} > 6 \times 10^4$), the horizontal temperature gradient becomes locally negative in some regions. This causes horizontal elongation of the streamlines and the development of a second roll in the core (Fig. 7.1b). By further increase of the Rayleigh number, a new flow regime is observed (Fig. 7.1c), with a strongly stratified temperature distribution in the center and thin thermal boundary layers at both isothermal side walls. This regime after increasing Rayleigh number above $10^8$ leads to a transition to turbulence. Such a transition, easily identified using full-field temperature visualization and quantification, can be directly compared with numerical simulations of the corresponding cases.

Flow visualization via liquid crystals allows the observation of the flow structure and identification of variation of the temperature field. Even without quantitative data, the general shape of the isotherms can be deduced from the color photographs. However, despite the undoubted beauty of multiply exposed color photographs of liquid-crystal tracers, they have little value for quantitative image analysis. The lack of visible particles in large regions of the flow and their individual modulation of color are the main obstacles to computerized analysis. Hence, digital images of flow taken to implement particle image velocimetry and thermometry analysis exhibit a rather dense, uniform crowd of small, singly exposed colorful dots, representing a fine dispersion of the liquid-crystalline material in the flow. The human eye may still easily analyze the color distribution of such images (Fig. 7.5c), but particle displacements can be detected only by computational means.

The behavior of natural convection of water in the vicinity of the freezing point shows an interesting feature in the typical configuration with differentially heated walls. It is mainly due to the strongly nonlinear temperature dependence of the density function, which has an extremum at $4\,^\circ\text{C}$. The competing effects of positive and negative buoyancy force result in a flow with two distinct circulations. There is a *normal* clockwise circulation, where the water density decreases with temperature (upper-left cavity region) and an *abnormal* convection with the opposite density variation and counterclockwise rotation (lower-right region). As mentioned, TLCs allow
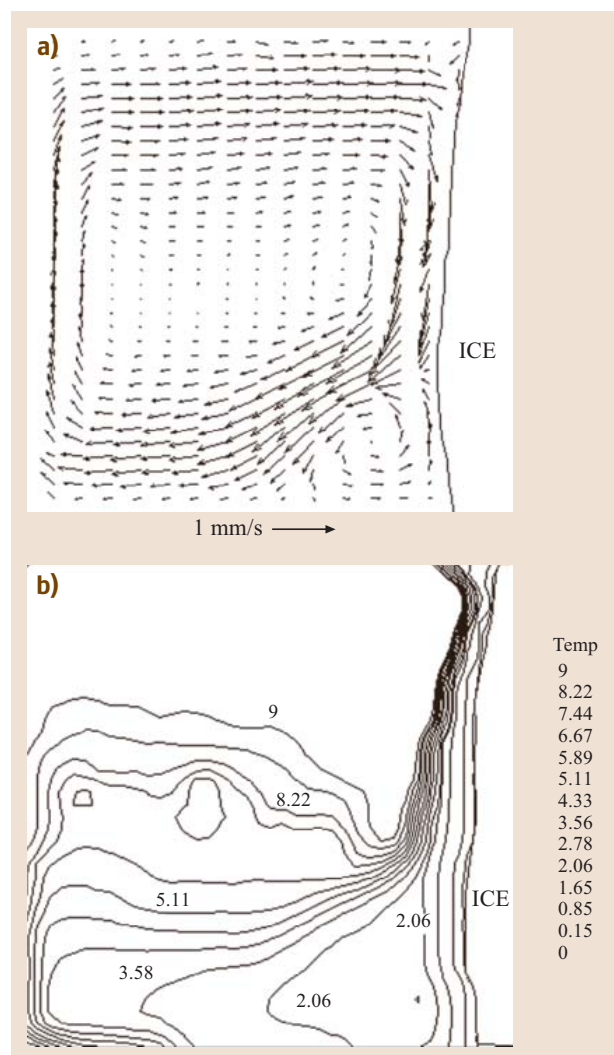


**Fig. 7.6a,b** Particle image velocimetry (**a**) and thermometry (**b**) applied to measure the velocity and temperature fields for natural convection in water freezing in a differentially heated cavity. Temperatures applied: $10\,^\circ\text{C}$ (on the left wall) and $-10\,^\circ\text{C}$ (on the right wall)

the detection of temperature over a limited range of their color play regime. In some cases it is necessary to obtain precise information over a wider range of temperature variation, a task that is impossible to achieve with high precision for a single brand of TLCs. For steady or reproducible flow configurations it is possible to repeat the same experiment using different types of TLCs, as illustrated in Fig. 7.5. Regions of low temperature are visualized in Fig. 7.5a using TLCs operating in the temperature range $0-4$ °C, and the same experiment is repeated in Fig. 7.5b to elucidate the temperature pattern in the left part of the cavity, using other types of TLCs.

To investigate natural convection with a phase change, one of the isothermal walls was held at a temperature of $T_c = -10$ °C. As this is below the freezing temperature of water, ice is formed at the cold wall (Fig. 7.5c). Initially uniform growth of the ice layer is quickly modified by the two colliding *normal* and *abnormal* circulations. In the upper part of the cavity, convective heat transfer from the hot wall is limited by the abnormal circulation, separating it from the freezing front. Figure 7.6 demonstrate the ability of TLCs to resolve simultaneously the transient variation of the velocity and temperature fields. These data, which were compared with numerical simulations performed for the freezing problem [7.24], led us to discover significant discrepancies and indicated directions to improve the model [7.27–29].

In the second solidification experiment flow in a cube with only one isothermal wall was investigated. The top isothermal wall was kept at a low temperature and the other five walls were nonadiabatic, allowing a heat flux from the fluid surrounding the cube. The temperature at the internal surfaces of the cube adjusted itself depending on both the flow and the heat flux through and along the walls. The lid-cooled cubic cavity was selected to investigate the convective flow with and without a phase change (freezing of water at the top wall). When the phase change occurs, the configuration resembles to some extent a directional solidification in a Bridgman furnace used for crystal growth (Fig. 7.7). Physically this configuration bears some similarity to the Rayleigh–Bénard problem. The symmetry of the enclosure imposes a strong downward flow along the vertical axis of symmetry. However, before a stable final flow structure is achieved, several oscillatory changes in its pattern are observed [7.30, 31]. The initial flow instabilities are seen well in the temperature and velocity fields visualized by TLCs in the box and could be confirmed in the numerical simulations. The formation of ice has been studied by decreasing the lid temperature to $-10$ °C. A complicated flow pattern with azimuthally varying structure was also reproduced in the star-like ice surface [7.32]. It was found that the creation of the ice layer at the lid has a stabilizing effect on the flow. This follows from the symmetry of the solid ice surface, which imposes the direction and character of the flow, eliminating the instabilities observed in the pure convective case. There is also a density inversion under the lid that decelerates the main jet and limits convective heat flux in that region [7.33].

Another example of the investigated configurations illustrates the simulation of flow characteristics accompanying the casting processes (Fig. 7.8). For this purpose
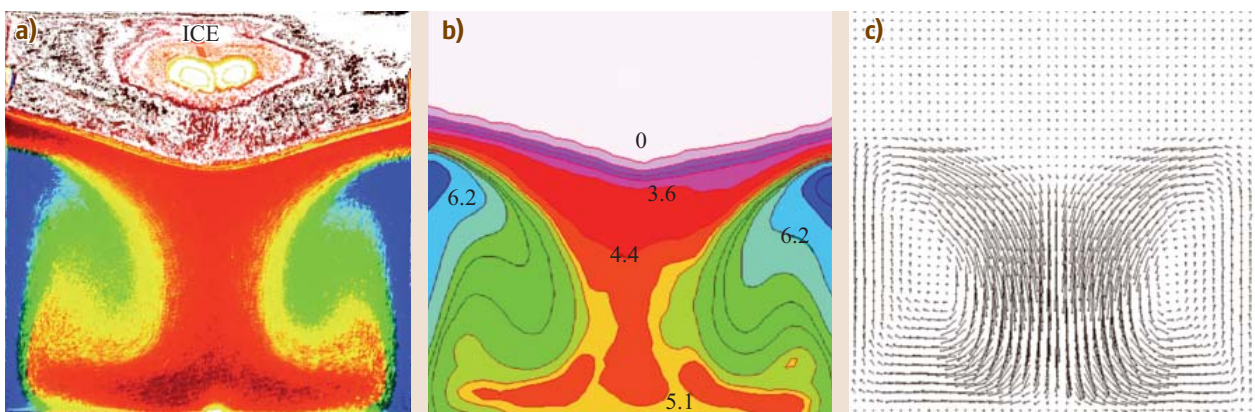


**Fig. 7.7a–c** Ice crystal growing from the top in a lid-cooled cavity in a Plexiglas cube immersed in an external water bath at a temperature of $20$ °C. The isothermal metal lid has a temperature of $-10$ °C. Unencapsulated mixture of thermochromic liquid crystals (TM445 and TM912) used as tracers to evaluate both the temperature and velocity flow fields. **(a)** Superposition of five recorded images taken every $400$ ms, **(b)** the evaluated temperature, and **(c)** the velocity fields
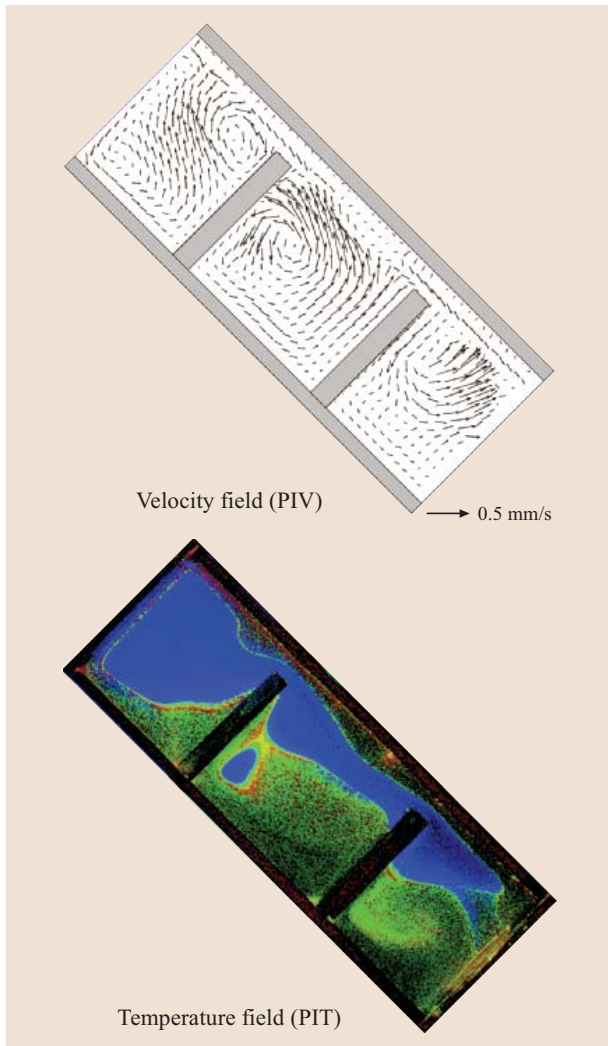
**Fig. 7.8** Velocity field and temperature distribution visualized for the cavity inclined at 45°. Two cold isothermal walls (upper and lower) are responsible for sudden cooling of the fluid. This changes the color of the seeded liquid crystals (TM446) from blue (hot) to red (cold regions)

a rectangular cavity with two isothermal walls was filled with pressurized hot, viscous liquid (glycerol). The main features of the experiment, such as flow acceleration and deceleration at obstacles, a free surface flow and a sudden increase of the fluid viscosity on cooling, are typical for melt solidification in a mould. In contrast to a real casting, use of TLCs as tracers enables full-field measurement of the temperature and velocity fields. Quantitative transient data for the velocity and temperature fields were collected to verify and validate the numerical models used for typical casting problems. The main aim of the investigation was to

create an experimental benchmark for the mould-filling problem [7.25, 34].

A similar rectangular, inclined box filled with water was used to simulate the up-slope, down-slope flow transition, typical for natural convection of air in valleys. Despite the differences in scales, some atmospheric phenomena, such as updraughts typical of the morning transition, down-slope front propagation during the evening transition, and nocturnal stable stratification can be visualized well in the laboratory experiment. To investigate up-slope flow phenomenon a negative temperature gradient is set up between the lower and upper wall, simulating solar heating of the ground. For transition and down-slope flow studies the temperature of the walls is reversed by switching the coolant settings. TLC tracers changing the color of refracted light with temperature indicate the onset of flow instabilities with periodically rising plumes and hot fluid ejections, analogous to those observed for diurnal circulation on long, sloping surfaces (Fig. 7.9). These periodical ejections could be identified well in the experimentally measured velocity fields and reproduced in the numerical simulation. After reversing the temperature gradient a transition front was observed both in the temperature field and the velocity field. The front builds up about 1 min after the reversal of temperature of the walls at a distance of 2 cm from the lower edge of the slope, and disappears about 5 min later, when regular nocturnal stratification of the temperature and the flow pattern develops [7.35].

## 7.1.5 Conclusions

Application of TLC tracers to laboratory studies of thermally driven flows appears to be, in most cases, the only option for acquiring full-field information about the temperature and velocity fields in liquids. The noninvasive character of the method and its relative simplicity enables a valuable tool for the full-field verification and validation of numerical results for small-scale laboratory configurations. We found that a large improvement in the quality and reliability of numerical simulations could be obtained by validating and tuning methodologies using information obtained from the full-field flow measurements described [7.36].

However, despite its apparent simplicity, TLC thermography requires tedious and frequently repeated calibrations to offer high-quality quantitative measurements. This is especially true for applications involving flow field measurements. Further investigations both in improving TLC stability and the robustness of color evaluation procedures are necessary.
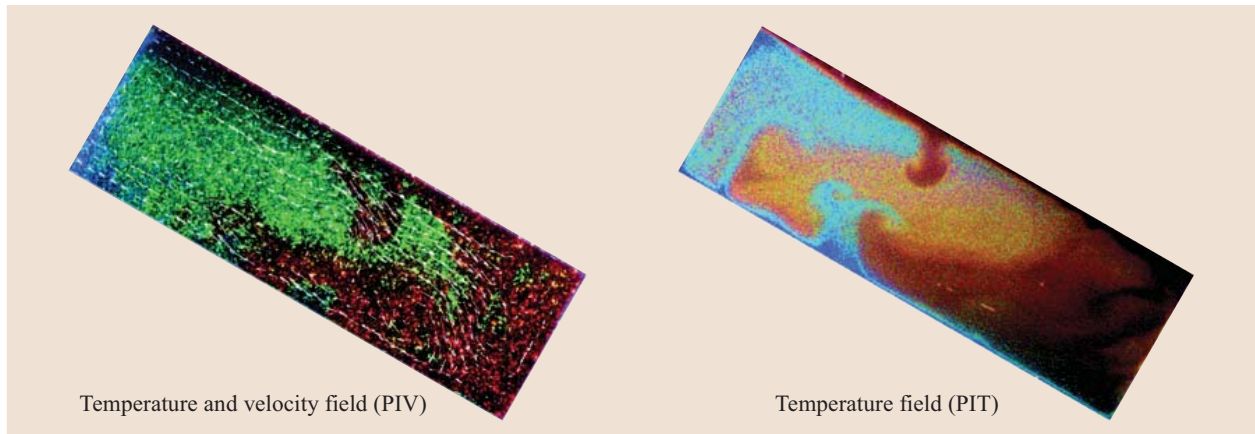
**Fig. 7.9** Laboratory simulation of a diurnal up-slope flow, temperature and velocity measured with TLCs suspended in water. *Left*: unencapsulated tracers TM107 used to evaluate temperature and velocity fields in the cavity inclined at 30°; *right*: encapsulated tracers (TCC1001) visualizing the temperature field in the cavity inclined at 20°

## 7.2 Measurements of Surface Heat Transfer Characteristics Using Infrared Imaging

### 7.2.1 Introduction and Background

The use of infrared thermography has increased dramatically throughout the world over the past 15 years for the measurement of surface characteristics for a variety of research investigations involving convective heat transfer phenomena. The technique is especially viable and useful because it gives spatially resolved surface temperature distributions non-intrusively, even when large gradients of surface temperature are present. This can be done with high levels of accuracy and resolution, when the infrared imaging system and acquisition procedures are properly calibrated, and the nuances of camera behavior and infrared imaging are properly taken into account. In many research situations, the surface temperature distribution itself is of interest. However, its measurement is often one step in the determination of a variety of other spatially varying quantities that may be of interest, such as surface heat transfer coefficient distributions, nondimensional quantities containing surface heat transfer coefficients, surface adiabatic effectiveness, overall thermal effectiveness distributions, and thermal boundary condition information for numerical predictions of arrangements that are measured experimentally.

One critical step in the use of infrared thermography is the calibration of the images in some way

so that local surface temperatures can be determined from the different shades, gray scales, or colors within infrared images. This is possible analytically, but requires knowledge of a variety of physical characteristics such as the surface emissivity, the effective atmospheric transmittance, the temperatures of surrounding walls, the atmospheric temperature, and other quantities. Because of the complexity and limited accuracy that is possible with such an approach [7.37], most investigators use some form of in situ calibration instead. Such an in situ calibration procedure was described and used as early as 1968 by *Czysz* and *Dixon* [7.38] for surface measurements using thermographic phosphors. Details of in situ calibration procedures employed by other investigators for specific measurement apparatus and environments using infrared thermography are described by *Meyers* et al. [7.39], *Gartenberg* and *Roberts* [7.40], *Wendt* [7.41], *Westby* [7.42], *Martiny* et al. [7.43], *Sargent* et al. [7.44], *Schulz* [7.37], and others. In the *Meyers* et al. [7.39] study, film cooled combustor walls are investigated under transient conditions. During heating of the combustor, these investigators recorded data simultaneously from both the infrared camera scanner and thermocouples that were embedded in the walls of the chamber. These data were then used for a best-fit approximation of the calibration parameters of the camera. *Westby* [7.42] calibrates prior to measurements by stepping a test article through a series of indepen-