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THERMOCHROMIC LIQUID CRYSTALS IN HEAT TRANSFER RESEARCH

In recent years Thermochromic Liquid Crystals (TLC) have been successfully used in non-intrusive heat transfer and fluid mechanics studies. Thin coatings of TLCs at surfaces is utilised to obtain detailed heat transfer data of steady or transient process. Application of TLC tracers allows instantaneous measurement of the temperature and velocity fields for two-dimensional cross-section of flow. Computerised flow visualisation techniques allow automatic quantification of temperature of the analysed surface or the visualized flow cross-section. Here we present the review of the development of automated techniques for analysing thermal and flow images we used over past 15 years. The methods are based on computerised true-colour analysis of digital images for temperature measurements and modified Particle Image Velocimetry used to obtain the flow field velocity. Examples given for both surface and flow field measurements demonstrate significance of the method for validation of numerical codes.

1. INTRODUCTION

Liquid crystals are highly anisotropic fluids that exist between the boundaries of the solid phase, and the conventional, isotropic liquid phase. The TLC based temperature visualisation is based on the property of some cholesteric and chiral-nematic liquid crystal materials to reflect definite colours at specific temperatures and viewing angle. The colour change for the TLC ranges from clear at ambient temperature, through red as temperature increases and then to yellow, green, blue and violet, turning to colourless (isotropic) again at a higher temperature. The colour-temperature play interval depends on the TLC composition. It can be selected for bands of about 0.5°C to 20°C, and working temperature of -30°C to above 100°C. These colour changes are repeatable and reversible as long as the TLCs are not physically or chemically damaged. The response time of TLCs equals about 10ms. It is short enough for typical thermal problems in fluids. Since the colour change is reversible and repeatable, they can be calibrated accurately with proper care and used in this way as temperature indicators. They can be painted on a surface or suspended in a fluid and used to indicate visibly the temperature distribution. In this way, liquid crystals have been successfully applied to heat transfer and fluid flow research.

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During the past liquid crystals have been extensively applied to the qualitative visualisation of entire steady state, or transient temperature fields on solid surfaces. Since quantifying colour is difficult and somewhat ambiguous task, application of thermochromic liquid crystals initially was largely qualitative. Application of the colour films or interference filters was tedious and inaccurate. First application of true-colour digital image processing gave impact to qualitative and fast temperature measurements. Rapid development of the hardware and software image processing techniques made possible now to set-up inexpensive system capable for real-time transient full field temperature measurements using TLCs.

In this paper we review the above issues, and use illustrative examples from our own work in applying TLC to the study of forced and natural convective heat transfer, on a cooled surface heated by air flow disturbed by a number of complex geometrical configurations, and for temperature and flow visualisation in closed cavities also with phase change. Significance of the full field temperature and flow measurements for verification of numerical results becomes evident.

2. LIQUID CRYSTALS THERMOGRAPHY

Liquid crystals are temperature indicators that modify incident white light and display colour whose wavelength is proportional to temperature. They can be painted on a surface or suspended in the fluid and used to make visible the distribution of temperature.

Normally clear, or slightly milky in appearance, liquid crystals change in appearance over a narrow range of temperature called the "colour-play interval" (the temperature interval between first red and last blue reflection), centred around the nominal "event temperature". The displayed colour is red at the low temperature margin of the colour-play interval and blue at the high end. Within the colour-play interval, the colours change smoothly from red to blue as a function of temperature (Fig. 1) [15,29,30]. Pure liquid crystal materials are thick, viscous liquids, greasy and difficult to deal with under most heat transfer laboratory conditions. The TLC material is also sensitive to mechanical stress. A micro-encapsulation process which encloses small portions of liquid crystal material in polymeric material was introduced to solve problems with the stress sensitivity as well as with the chemical deterioration. For surface temperature measurements application of the unencapsulated material (unsealed liquids) to a clear plastic sheet and sealing it with a black backing coat to form a pre-packaged assembly is used. Commercially are available temperature indicating devices using TLC contain a thin film of the liquid crystal sandwiched between a transparent polyester sheet and a black absorbing background, however in the current experiment the liquid crystals are deposited on the black painted sheet.

For flow analysis the suspension of thermochromic liquid crystals can be used to make visible the temperature and velocity fields in liquids. By dispersing the liquid crystal material into the liquid they become not only classical tracers used for flow visualisation but simultaneously small thermometers monitoring local fluid temperature [1,16-21,30,34]. The collimated source of white light must be used to illuminate selected cross-section of the flow (light sheet technique) and colour images are acquired at the perpendicular direction.

In the following examples the unencapsulated TLCs tracers have been applied to measure both temperature and velocity flow fields. We found that light scattered by the capsule shell inevitable diminishes saturation of the observed colours. Because for slow motion the stress effects are negligible we prefer application of fine dispersed raw material in flow measurements.

2.2 SURFACE TEMPERATURE MEASUREMENTS

Before the execution of a thermal or flow visualisation experiment, we should recognise the characteristics of the overall combination of the TLC, the light source, the optical and camera system, and make a rational plan for the total measurement system. The relationship between the temperature of the crystal and the measured Hue of the reflected light defines the calibration curve for the liquid crystal. The result is a curve relating the Hue of the reflected light to the surface temperature. A known temperature distribution exists on a "calibration plate" (brass plate) to which is attached the liquid crystal layer.

In order to maintain a linear temperature distribution with desired temperature gradients, one end of a brass plate was cooled by stabilised water and the other end controlled electrically to give a constant temperature [2,34]. The brass plate with the liquid crystal layer is calibrated in place in the wind tunnel with the same lighting level and viewing angle used during the data acquisition phase of the experiment. The distribution of the colour component pattern on the liquid crystal layer was measured by RGB colour camera and a series of images at different temperatures defines the calibration. A representative calibration curve including Hue and temperature distribution along the plate is shown in Fig. 2 [35,36].

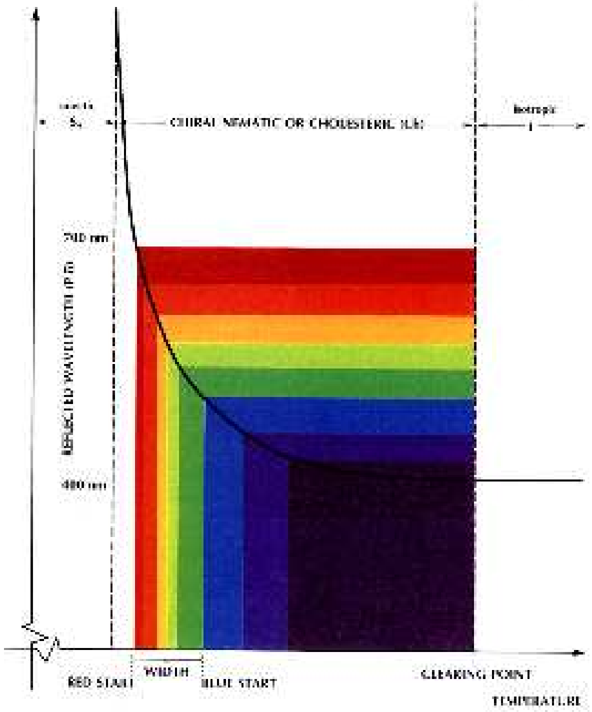


Fig. 1 Typical reflected wavelength (colour) temperature response of a TLC mixture.

The liquid crystals used here, manufactured in sheet form by B & H Limited (Fig. 3), had an event temperature range of 30.7 - 33.3°C. In the actual measurements, only the yellow-green colour band corresponding to t_l = 32.1°C was used as it is the brightest and sharpest. In this particular experiment uncertainty was estimated as about $\pm$ 0.05°C by considering only the section of the surface used in the experiment, spanwise non-uniformities in Hue value are minimized.

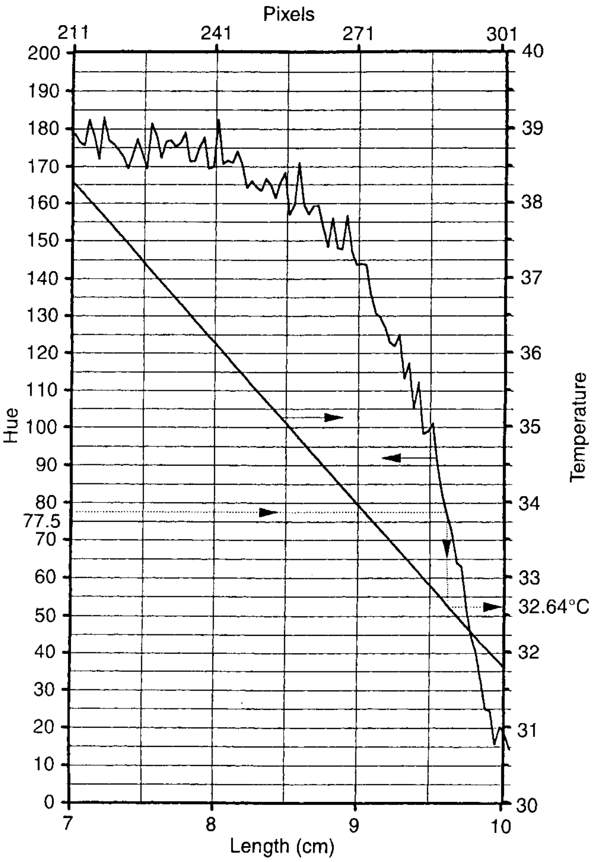


Fig. 2 Representative calibration curve - Hue and temperature distribution along the test plate

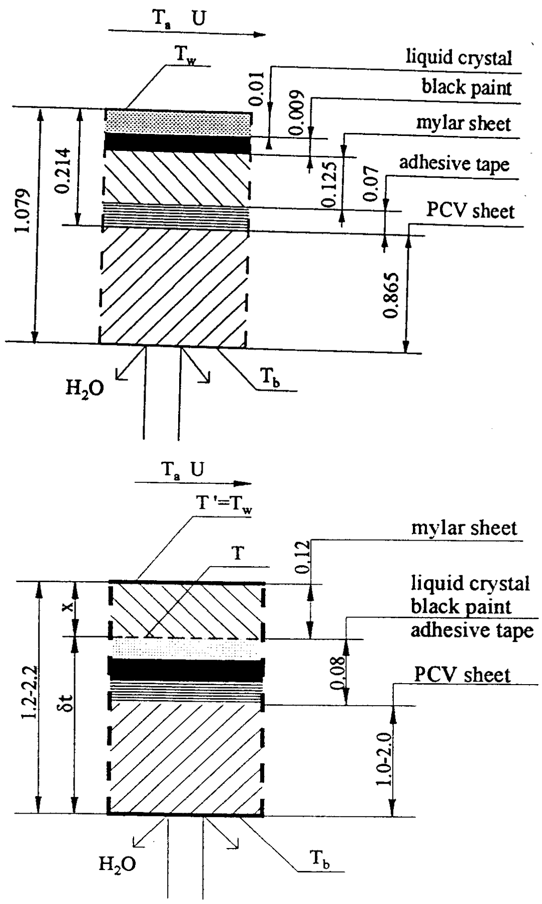


Fig. 3. Liquid crystal package, front print and waterproof

2.3 FLOW FIELD MEASUREMENTS

2.3.1 Particle Image Thermometry

Successful use of TLCs to map temperature distribution on surfaces, valuable for calculating heat transfer coefficients, induced their applications in fluid mechanics. Applications of TLCs tracers for flow and temperature visualisation [10,17-19,42] initiated development of Particle Image Velocimetry and Thermometry (PIVT) technique. Application of digital image analysis techniques gave impact to quantitative and fully automatic temperature and velocity evaluation based on Digital Particle Image Velocimetry [41] and Digital Particle Image Thermometry [11]. Employment of both digital evaluation techniques [21] allowed us simultaneous and fully automatic measurements of temperature and velocity fields for selected 2-D flow cross-section both for single phase flow as well as for natural convection with phase change (freezing of water) [24-26].

Application of the PIVT method for the phase change problems yields several additional experimental constrains. The investigated temperature range is well defined by the phase change temperature. Hence the colour-play properties of the TLC material have to be correctly matched. In addition, the solidus surface generates additional light scattering and reflections. These may generate unexpected colour shifts or/and image distortions in regions adjoining the phase front, and have to be accounted for throughout the calibration procedure.

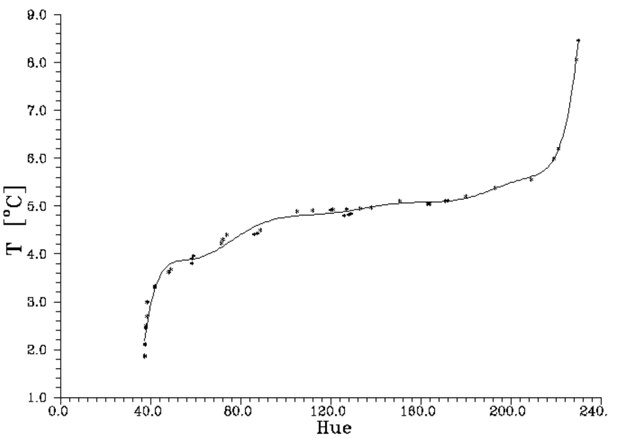


Fig. 4 Temperature vs. Hue for TLC sample. Calibration curve obtained by 8th order polynomial fitted to the experimental points.

In most of the flow experiments we use dispersed raw TLC material. The mean diameter of the unencapsulated TLC tracers used is about 50μm. The temperature measurements are based on a digital colour analysis of *RGB* images of the TLCs seeded flow field. For evaluating the temperature the *HSI* representation of the *RGB* colour space is used. The incoming *RGB* signals are transformed pixel by pixel into *Hue, Saturation and Intensity*. Temperature is determined by relating the hue to a temperature calibration function [25,26].

Comparing with the surface thermography, the use of TLCs as an dilute suspension in fluid bears additional problems. First of all the colour images of the flow are discrete, i.e. they represent non-continuous mist of points. Secondly, due to the secondary light scattering, its reflections from the side walls and internal cavity elements, the overall colour response may be distorted. Hence, use of specially developed averaging, smoothing and interpolating techniques are indispensably to remove ambiguity of resulting isotherms. Beside, every experimental set-up needs its own calibration curve obtained from the images taken for the same fluid, at the same illumination, acquisition and evaluation conditions.

Our 8-bit representation of the hue value assures resolution better than 1%. However, the colour - temperature relationship is strongly non-linear (Fig. 4). Hence, the accuracy of the measured temperature depends on the colour (hue) value, and varies from 3% to 10% of the full colour play range. For the TLCs used (TM from Merck) it results in the absolute accuracy of 0.15°C for lower temperatures (red-green colour range) and 0.5°C for higher temperatures (blue colour range). The most sensitive region is the colour transition from red to green and takes place for a temperature variation less then one Celsius degree. To improve the accuracy of temperature measurements, experiments have been repeated using four different types of TLCs, so that their combined colour play sensitivity covered wide range of temperatures, e.g. from -5°C to 14°C for freezing experiments.

The colour of light refracted by TLCs depends also on the refraction angle. Our previous investigations [18] have shown that the evaluated temperature depends linearly on the refraction angle, typically with the slope equal 0.07°C per 10° change of the view angle. Therefore, it is important that the angle between illuminated plane (light sheet plane) and the camera is fixed and the observation angle of the lens is small. In our experiments flow was observed at 90° angle using 50mm lens and 1/3' sensor, i.e. the full observation angle is smaller than 4°.

2.3.1 Particle Image Velocimetry

The 2-D velocity vector distribution has been measured by digital particle image velocimetry (DPIV). By this method, the motion of the scattering particles, observed in the plane of the illuminating light sheet, are analysed. For this purpose, the colour images of TLC tracers are transformed to B&W intensity images. After applying special filtering techniques [26] bright images of the tracers, well suited for DPIV, are obtained.

The magnitude and direction of the velocity vectors are determined using a FFT-based cross-correlation analysis between small sections (interrogation windows) of one pair of images taken at the given time interval. The average particle displacement during a given time interval determines the velocity vector representing the section investigated. Through a moving (step by step) interrogation widow across the image, about 1000 vectors per one pair of images are obtained. The spatial resolution of the method is limited by the minimum amount of tracers present in the interrogation window. In practice, the minimum window size was 32x32 pixels. On the other hand, the dimension of the interrogation window limits the maximum detectable displacement. Hence, to improve the accuracy and dynamics of the velocity measurements short sequences of images have been taken at every time step. The cross-correlation analysis performed between different images of the sequence (time interval between pairs changes), allows us to preserve similar accuracy for both the low and high velocity flow regions.

For some experimental data, the newly developed ODP-PIV method [31] of image analysis has been also used to obtain dense velocity fields of improved accuracy. In the cited paper results of several accuracy tests performed for the artificial images are given. It came out that for typical experimental conditions, i.e. images with 5% noise added and 5% particle disappearance, the accuracy of the „classical" FFT-based DPIV and that of the ODP-PIV method is 0.6 pixels and 0.15 pixels, respectively. It means that for typical displacement vector of 10 pixels the relative accuracy of the velocity measurement (for single point) is better than 6%.

To get a general view of the flow pattern, several images recorded periodically within a given time interval have been added in the computer memory. Displayed images are similar to the multiexposed photographs, showing the flow direction and its structure. This type of visualisation is very effective in detecting small re-circulation regions, usually difficult to identify in the velocity field. In all cases studied the volume concentration of tracers was very low (below 0.1%), so their effect on the flow and the physical properties of fluid was negligible small.

3. EXPERIMENTAL TECHNIQUES

3.1 SURFACE TEMPERATURE MEASUREMENTS

Many image processing operations developed for processing grey-level (intensity) images can be readily applied to HSI colour images. These include image transformations, enhancement, analysis, compression, transformation and restorations. Building on grey-scale image processing hardware and software, Data Translation has produced a 512 x 512 pixels x 8 bit per colour component colour frame-grabber board for PC/ATs which takes up a 256 K byte of memory [12]. A schematic view of such an image processing system (used

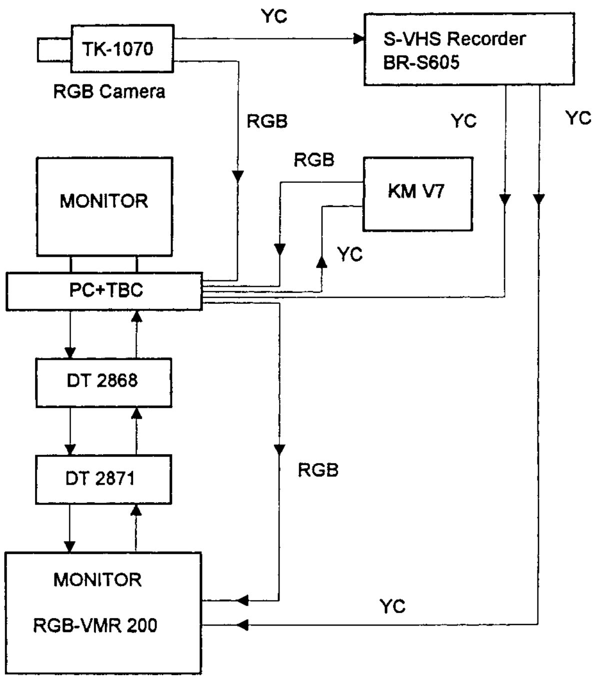


Fig. 5 The information flow chart for a true-colour image interpreter and computer-controlled video system

The two dimensional temperature distribution is determined using RGB video-camera, IBM 386 Personal Computer AT, HSI Colour Frame Grabber DT 2871 and Auxiliary Frame Processor DT 2858. As shown, the chart is also for a S-VHS video-recorder (JVC-S605E), includes a Time Based Corrector VT 3000 and KMV7EK RGB convertor. New chart with JVC-S605E as the terminal makes it possible for presentation tapes to be loaded, cued and played exactly on schedule with all operation handed by the computer. For fast and transit method, accurate location of specific scenes or edit points JVC-S605E is provided with a convenient, easy-to-use search dial. A time base corrector (TBC) controls times tracking systems and easy identification colour-coded images.

Two main methods of surface temperature measurement are performed involving steady state and transient techniques. A brief history of these is given by Baughn et al [6]. Recent reviews of heat transfer measurements have also been produced by Moffat [29], Jones et al [23], Ashforth-Frost et al [4] and Stąsiek [37].

(a) Steady State Analyses - Constant Flux Method

The steady state techniques employ a heated model and the TLC is used to monitor the surface temperature. Usually, a surface electric heater is employed such that the local flux, q is known and this, together with the local surface temperature, T_w, (found from the TLC), gives the local heat transfer coefficient, h,

$$q = I^2 r \text{ and } h = \frac{q}{T_a - T_w}$$

T_a is a driving gas temperature, I is the current and r is the electrical resistance per square of the heater.

(b) Steady State Analyses - Uniform Temperature Method

The TLC-coated test specimen forms one side of a constant temperature water bath and is exposed to a cool/hot air flow. The resulting thermograph is recorded on film or video and further measurement positions are obtained by adjusting the water bath temperature. This method is more time consuming due to the large volume of water that needs to be heated. In this case, the heat transfer coefficient is determined by equating convection to the conduction at the surface,

$$h(T_a - T_w) = \frac{k}{x}(T_w - T_b)$$

where, T_b is a water-side temperature of the wall, x the wall thickness and k the thermal conductivity.

(c) Transient Method

This technique requires measurement of the elapsed time to increase the surface temperature of the TLC-coated test specimen from a known initial temperature predetermined value [6,22,23]. The rate of heating is recorded by monitoring the colour change patterns of the TLC with respect to time. If the specimen is made from a material of low thermal diffusity and chosen to be sufficiently thick, then the heat transfer process can be considered to be one-dimensional (1-D) in a semi-infinite block. Numerical and analytical techniques can be used to solve the 1-D transient conduction equation. The relationship between wall surface temperature, T, and heat transfer coefficient, h, for the semi-infinite case is,

$$\frac{T - T_i}{T_a - T_i} = 1 - e^{\beta^2}\mathrm{erfc}(\beta); \; \beta = h\left(\frac{t}{\rho c k}\right)^{0.5}$$

where, ρ, c and k are the model density, specific heat and thermal conductivity. T_i and T_a are the initial wall and gas temperatures and t is time from initiation of the flow [6,23]. More recently Leiner et al. [27] developed a new formula for evaluation of heat transfer coefficient h in following form :

$$h = -\frac{\delta \rho c}{t}\ln\left[\frac{T_a - T}{T_a - T_i}\right]$$

where, δ is a plate wall thickness and the transit local surface temperature T is detected after a time interval t.

3.2 Flow Measurements

The typical experimental set-up used for the flow measurements (Fig. 6) consists of a convection box (Fig. 7), a halogen tube lamp, the 3CCD colour camera (KYF55 JVC) and the 32-bit frame grabber (IC-PCI ITI). The flow field is illuminated with a 2mm thin sheet of white light from a specially constructed halogen lamp, and observed in the perpendicular direction. The 24-bit colour images of 768x564 pixels have been acquired using a 64MB Pentium 133 computer. This set-up permits us to gain in real time over 50 images before they have to be saved on the computer magnetic disk.

The convection cubic box, of 38mm inner dimension, has two (or one) isothermal walls made of a black anodised metal. Their constant temperature is maintained by an anti-freeze coolant flowing through the attached antechamber. Four non-isothermal walls of the cavity are made of 9mm thick Plexiglas. The temperature of the cooling and heating liquids and that of the water in the bath (eventually surrounding the four non-adiabatic walls) are controlled by thermostats. The computer controlled system of three stepping motors allows to acquire images of the several cross-sections, both for horizontal and vertical planes, fully automatically within several seconds. This allows three-dimensional analysis of the whole flow domain. The computer controls also switching of the halogen lamp and records readings from four control thermocouples and the thermostats.

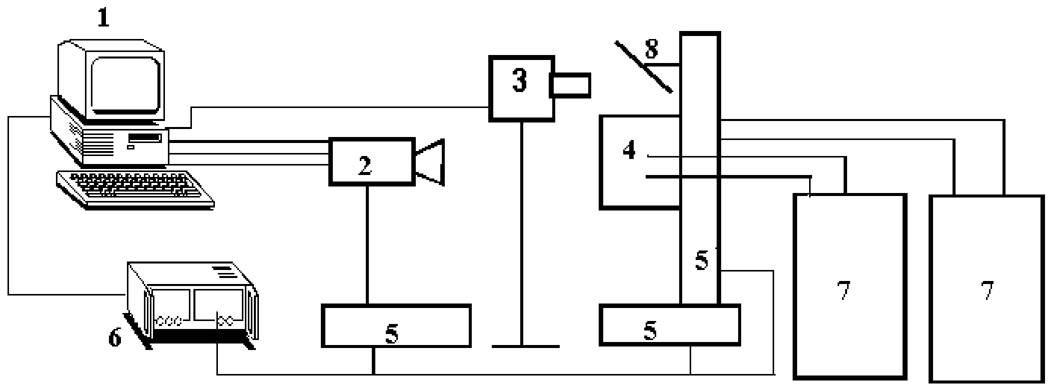
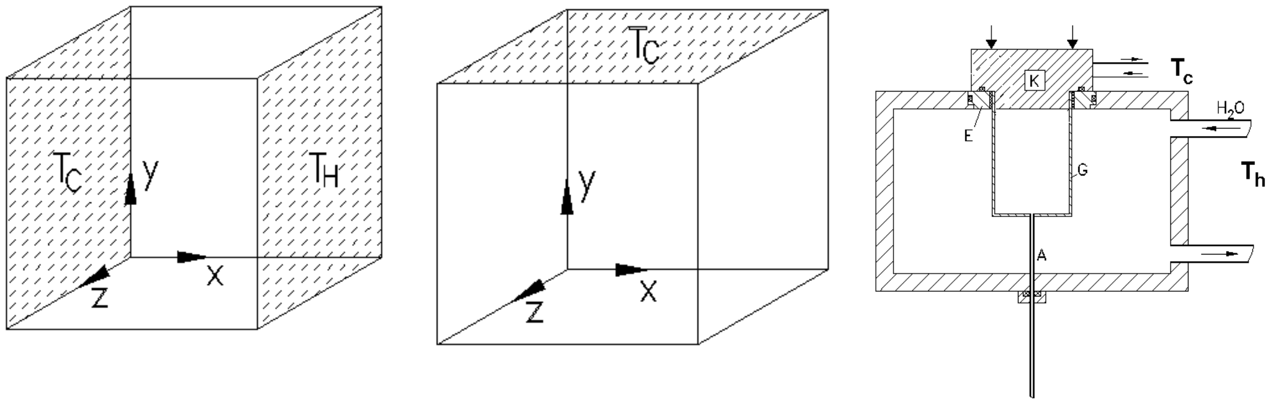


Fig. 6 Schematic of the experimental system. PC (1) with the acquisition card controlling camera (2), halogen lamp (3) and three stepping motors (5) using driver (6). Temperature in the cavity (4) controlled by two thermostates (7). Mirror (8) used to direct light sheet.



(a) (b) (c)

Fig. 7. Geometry of investigated flow systems: a - differentially heated box, b - lid cooled cavity (also cylindrical), (c) - schematic of heating for the lid cooled cavity with an isothermal top lid (K) immersed in the external hot water bath.

4. APPLICATION EXPERIMENTS

In order to demonstrate the feasibility of TLC techniques in practical heat transfer contexts the authors have performed several experiments. The first set was carried out to investigate temperature and heat transfer coefficient distributions on a cooled surface heated by an air flow and disturbed by a number of complex geometrical configurations, namely,

i. Cylinders (both single and double) and a square section column
ii. Square roughness elements and rib-roughened channel
iii. Crossed-corrugated and corrugated-undulated elements as used in rotary heat exchangers (regenerators) for fossil-fuelled power stations.

In the second set of experiments the flow velocity and temperature distribution in rectangular cavity were measured using unencapsulated TLC's.

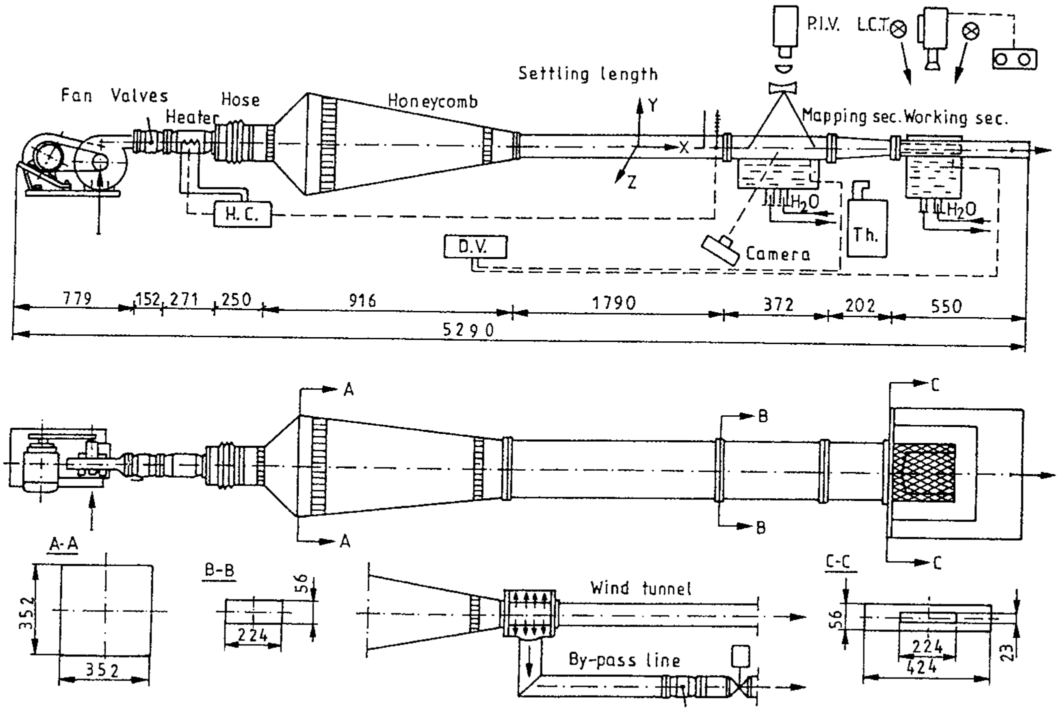
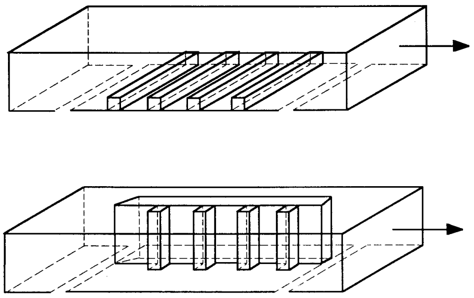


Fig. 8. Open low-speed wind tunnel

The experimental study was carried out using an open low-speed wind tunnel (Fig. 8), consisting of entrance section with fan and heaters, large settling chambers with diffusing screen and honeycomb, and then mapping and working sections Fig. 9 and Fig. 10. Air is drawn through the tunnel using a fan able to give Reynolds numbers of between 500 and 50,000 in the mapping and working sections. The working air temperature in the rig range between 25°C to 65°C produced by the heater positioned just down stream of the inlet. The major construction material of the wind tunnel is perspex. Local and mean velocity are measured using conventional Pitot tubes and DISA hot-wires velocity probe. The wind tunnel is instrumented with copper-constantan (Type T) thermocouples and resistance thermometers so that the surface, water bath and air temperatures can be measured and controlled by a Variac control system. The alternative effects of constant wall temperature and constant heat flux boundary conditions are obtained using a water bath, while the temperature can be controlled with a thermostat capable of establishing and maintaining temperature to within $\pm$ 0.01°C accuracy. Photographs are taken using a standard camera, RGB video-camera and true-colour image processing system. The heat transfer coefficient is a defined quantity, calculated from the surface heat flux and the difference between the surface temperature and some agreed reference temperature. This is usually the far field temperature, the mixed mean temperature or the adiabatic surface temperature. Liquid crystals can be used to determine the distribution of the surface temperature, and if the surface heat flux can be found, this allows evaluation of the heat transfer coefficient or the Nusselt number.



Mapping section geometries.

Fig. 9. Mapping section geometry with square roughness elements and rib-roughened channel

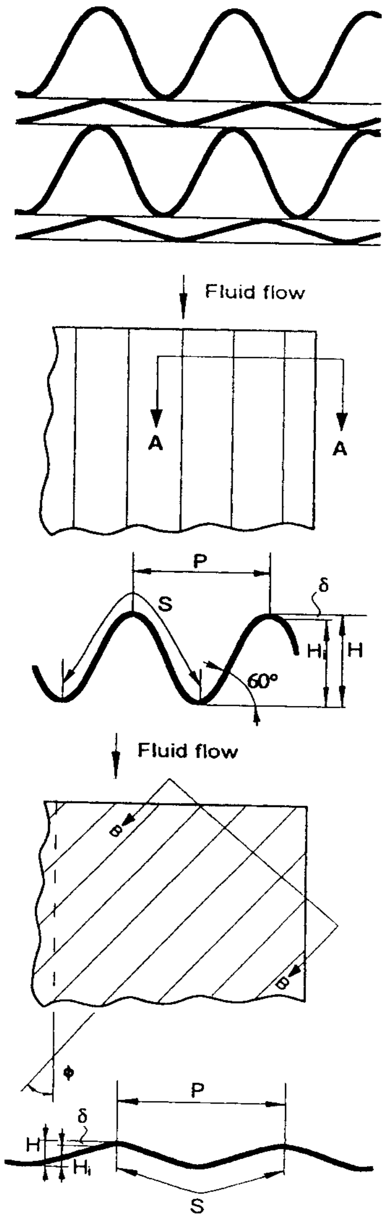


Fig. 10. Working section - general view of corrugated-undulated heat transfer element.

The alternative effects of constant wall temperature and constant heat flux boundary conditions are obtained using a water bath. Photographs are taken using a RGB video-camera and a true-colour image processing technique. Usually several isotherms (each corresponding to a different heat flux) are taken by RGB video-camera to record the local Nuselt contours under an oblique Reynolds number. The locations of each isotherm and colour (adjusted to each Nusselt number) are digitized following a projection of the false colour image on a digitizing image respectively (this particular method can be called "Image Combination Technique" ICT). Fig. 11 shows photographs of the colour distribution of the liquid crystal layer around square section column (top photo), image of the computer display after segmentation processing (Hue: 45-55) (middle photo) and false colour image processing (ICT) respectively on bottom photo. The colour image from the RGB camera and the segmentation monochrome line showing the 32.1°C isotherm for the double cylinders column at Re = $2.0 \cdot 10^4$ are presented together in Fig. 12. The image in Fig. 13 shows Nusselt number contours around double cylinders column processed by the ICT. Also (as mentioned above) liquid crystal thermography has been applied to the study of heat transfer by forced convection from a square roughness elements and rib-roughened channel. A sample of the results for these studies is shown in Figures 13 and 14. In these experiments a square element mounted horizontal and normal to the heated flat plate was employed as promotor of turbulence [42]. Recording the colour pattern by a RGB video-camera and converting the stored image to the HSI domain allows one to reconstruct the isotherm lines in the new colour scale (ICT) selected arbitrarily for better understanding and visualization of heat transfer and fluid motion

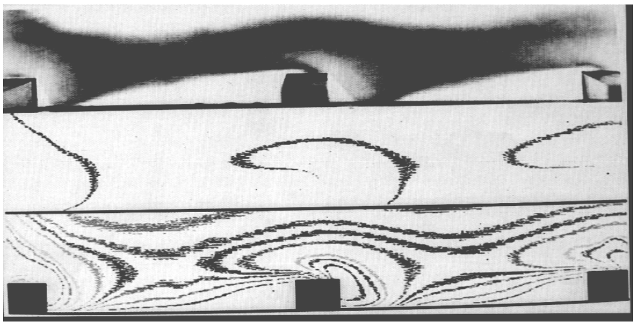


Fig. 11. Image processing steps: true-colour image of the test section under given flow and heating conditions (top), selection of the yellow-green colour band corresponding to a given Nu number value (middle), false colour image corresponding to the superposition of a number of lines at constant Nu number (bottom).

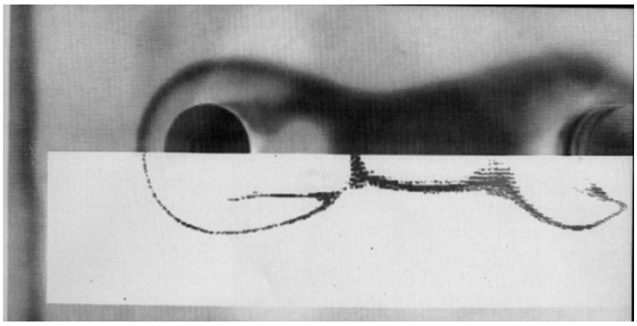


Fig. 12. Comparison between the image from RGB camera and the segmented monochrome 32.1 °C line for the double cylinders column at $Re=2.0\ 10^4$.

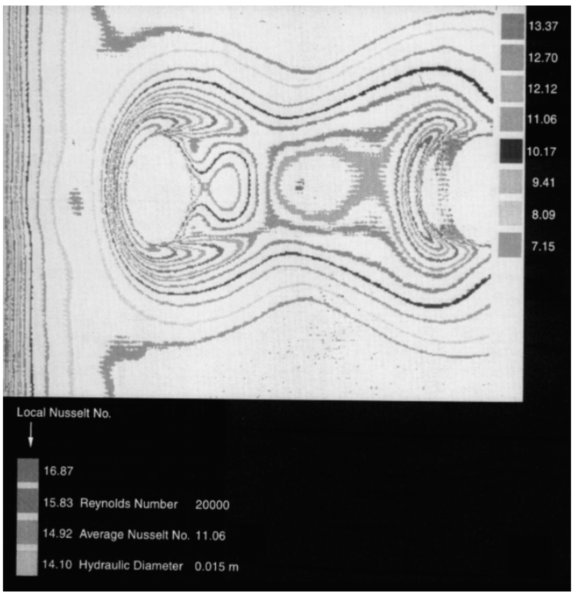


Fig. 13. Colour-scale representation of Nusselt number distribution around double cylinders column processed by image combination techniques

The first investigated geometry consisted of a plane heated wall with square ribs attached at regular intervals - the rib to height ratio was 7.2 for all experiments (Fig. 16. In Fig. 14 the Nusselt number distribution along the wall is reported and compared with interferometric data at the same Re number (between fourth and fifth ribs only). The profile obtained by LC analysis exceeds the interferometric results by 10-25 per cent. It should be pointed out that the geometric parameters (height and width of the channel) as well as thermal boundary conditions were not exactly the same in the two different set of experiments. In spite of this, the agreement is rather satisfactory and demonstrates the suitability of both techniques to gain quantitative information on heat transfer distribution in roughened surfaces. Also Fig. 15 shows a false colour image of local Nusselt number contours over a central diamond of the corrugated-undulated heat exchanger surfaces. The cross corrugated and corrugated-undulated surfaces are frequently employed to increase heat transfer coefficient for high heat flux applications (Fig. 10). Improvements in their flow and thermal characteristics does not require any demonstrations and would substantially reduce fuel and production costs.

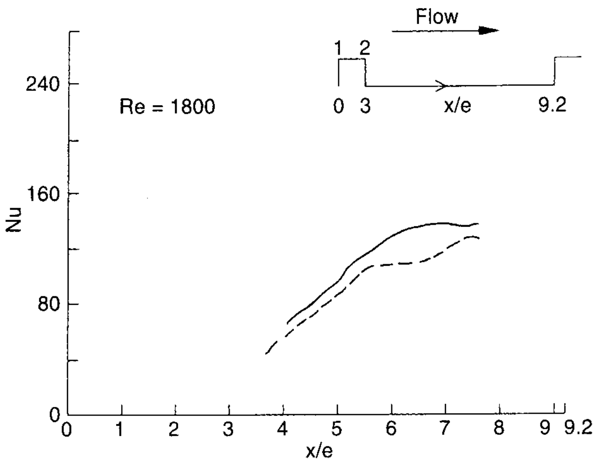


Fig. 14. Nusselt number distribution in the inter-rib region from liquid crystal data in comparison with interferometric data (Re=1.8 10^4). Continuous line: liquid crystals, dashed line: interferometry.

Fig. 15. False colour image of local Nusselt number contours over a central diamond of the undulated plate of corrugated-undulated geometry (ϕ=70°, Re=2080, H=8.8mm, L=32mm).

These considerations led to the execution of a comprehensive experimental and analytical investigation at City University supported by PowerGen U.K. [35]. The measuring technique comprising the use of LC flexible sheets and true-colour processing may also be used for a great variety of applications and should be of considerable use in improving the design of all types of compact heat exchanger. The distribution of the experimental and predicted local Nusselt number for cross-corrugated element is compared in Fig. 16. The computer aided analysis of colour images of micro-encapsulated TLC is a promising investigative method of two-dimensional surface temperature measurement.

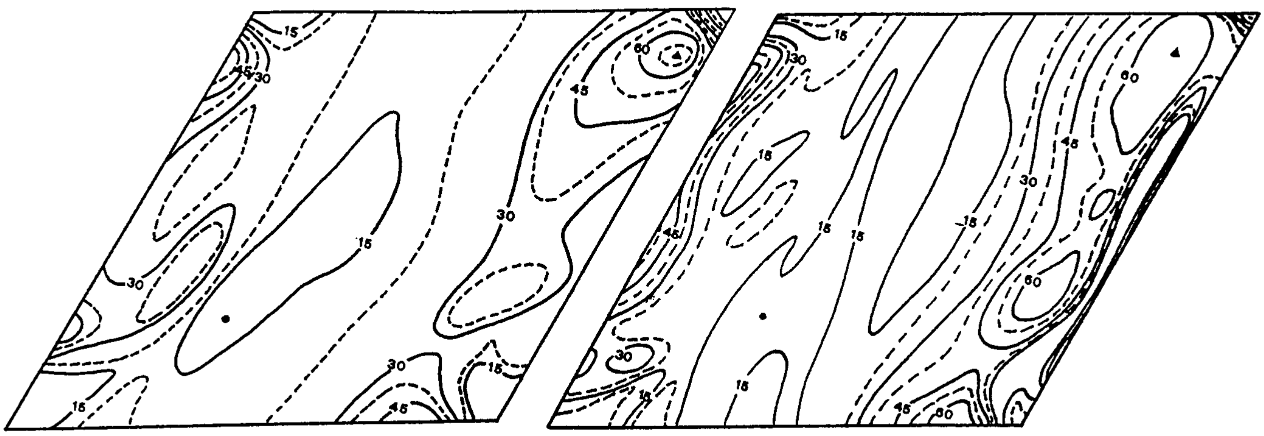


Fig. 16 Experimental and predicted distribution of the local Nusselt number on the top wall for a crossed-corrugated geometry (P/H=4, ϕ=70°, Re=2400).

4.2 NATURAL CONVECTION IN A CLOSED CAVITY

The first flow configuration concerns a popular „bench mark" case, low Rayleigh number natural convection in a cubical cavity with differentially heated end walls. Two opposite vertical walls are isothermal and kept at temperatures T_h and T_c, the other four walls are nominally insulators of finite thermal diffusivity.

evaluated from TLC images for the mid-plane of the half cavity taken for the vertical position [21].

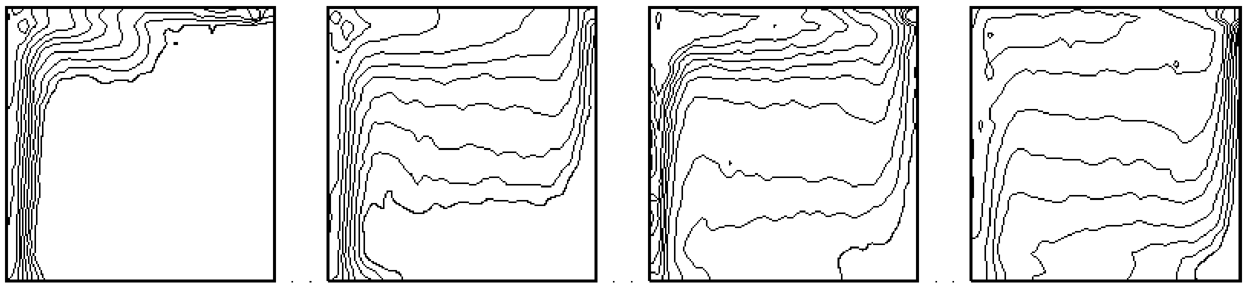
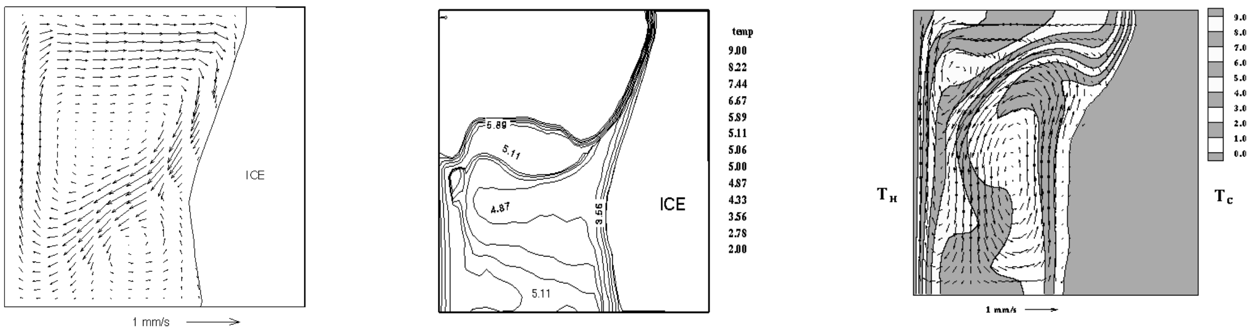


Fig. 17 Transient development of isotherms measured at the centre-plane of differentially heated cavity: time t=2min, 10min, 20min and 60min after the temperature T_h is applied; initial fluid temperature T_o = T_c; Ra=1.8·10^5, Pr=980.

Behaviour of natural convection of water in the vicinity of the freezing point show interesting future. Typical configuration with differentially heated walls was studied (Fig. 18). The experiments start by abruptly dropping the cold wall temperature to -10°C. A flow structure exhibits two circulation regions, where the water density decreases with temperature (upper) and an abnormal density variation (lower). This type of the flow structure appears very sensitive, and depends strongly on the modelling of the thermal boundary conditions at the side walls. Neither isothermal or constant heat flux models are sufficiently accurate to obtain observed flow structures. Full field flow measurements allowed us to discover main discrepancies and indicted directions of improving the model. The importance of the accurate description of the water density variation emerged, when several functions available in the literature were tested. Very small deviations in their functional form appeared to accomplish distinct changes in the flow structure [24].

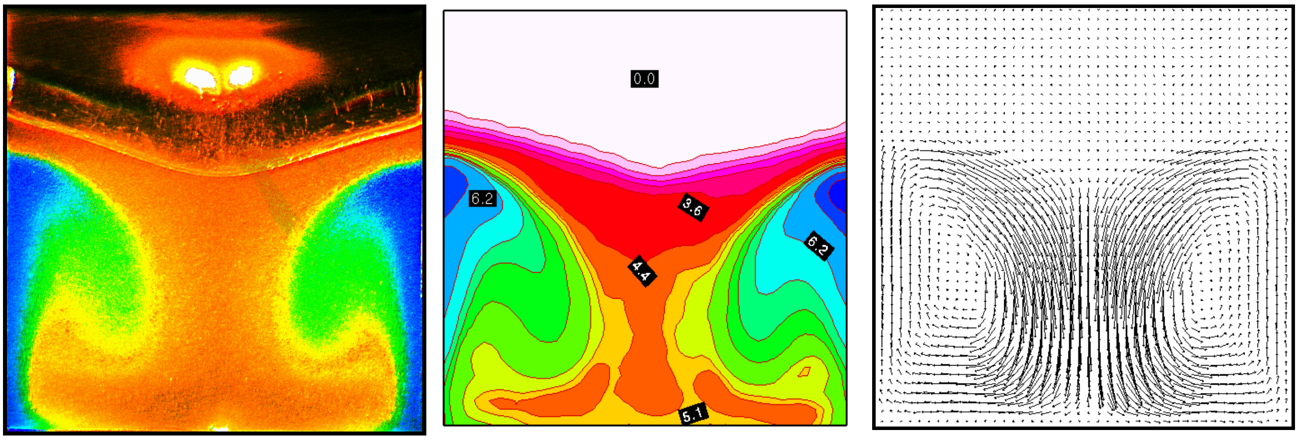


(a) (b) (c)

Fig. 18 Freezing of water form the left in the differentially heated cavity. Measured velocity (a) and temperature (b) fields; (c) - numerical calculated velocity and temperature fields. Time step - 2600s after cooling starts; T_c= -10°C, T_h= 10°C.

In the second configuration (Fig. 19), the top wall of the cube is isothermal at low temperature T_c. The other five walls are non-adiabatic, allowing a heat flux from external fluid surrounding the box. The temperature T_h of the external bath is kept constant. Due to forced convection in the bath it can be assumed that the temperature at the external surfaces of the box is close to the bath temperature. The temperature field at the inner surfaces of the walls adjusts

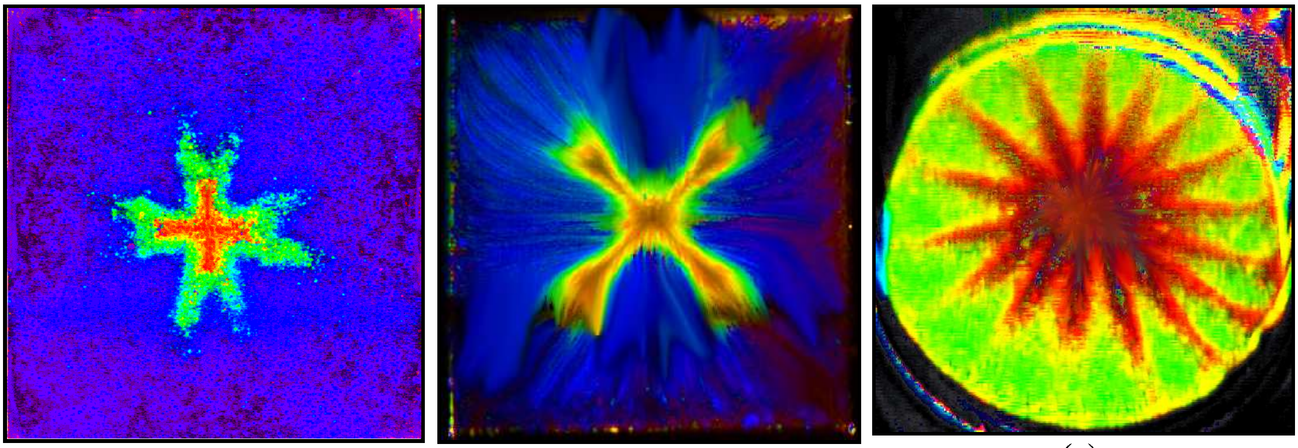
Both configuration were selected to investigate the convective flow with and without a phase change (freezing of water at the cold wall). To some extent they resemble a directional solidification in a Bridgman furnace used for crystal growth [26].



(a) (b) (c)

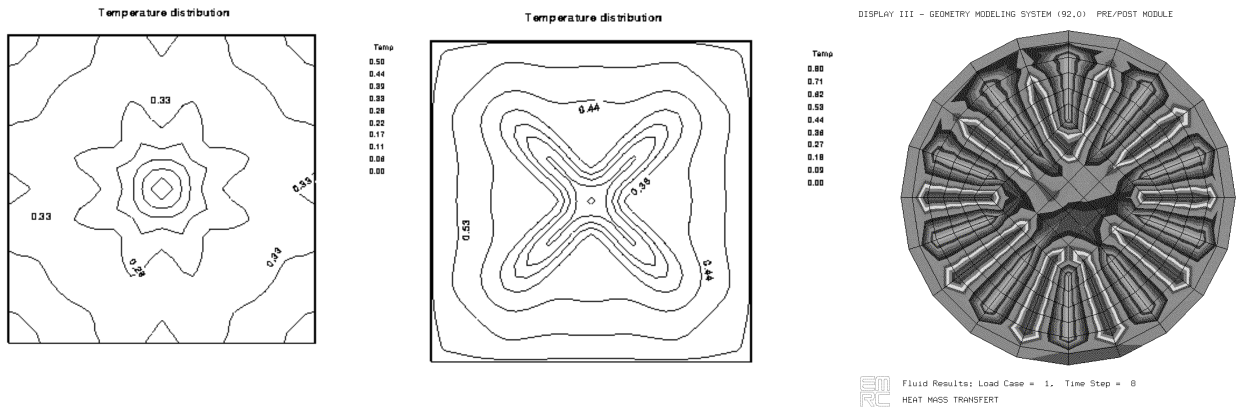
Fig. 19 Freezing of water from the top in the lid cooled cavity. Recorded image of TLC tracers (a), evaluated temperature (b) and velocity (c) fields. Time step - 3600s after cooling starts; T_c*= -10°C,* T_{ext}*= 20°C.*

The onset of convection and the stability of an initially isothermal fluid in a cubical box instantaneously cooled from above have been extensively investigated for water, both with and without phase change. Physically this configuration bears some similarity to the Rayleigh-Bénard problem. However, due to altered thermal boundary conditions at the side walls, the flow structure is different. The flow visualisations shown the existence of a complex spiralling structure transporting fluid up along the side walls and down in a central cold „jet" along the cavity axis. For walls of high heat conductivity (glass), eight symmetric cells were created by the flow. For Plexiglas walls additional small recirculation regions appeared separating the main cells. These structures reflect the temperature pattern recorded under the lid (Fig. 20 a, b). Numerical simulation has show discrepancies in the flow pattern. Although the computational results confirmed the eight-fold symmetry of the temperature and flow fields observed experimentally, their orientation was different. Moreover, the measured isotherms were evidently shifted to higher values. Serious discrepancies were noticed for temperature distribution observed at the horizontal cross-section. It was found that heat flux through and along the walls needs to be properly modelled too. Only a slight change of the *thermal boundary conditions* at the side walls may modify the flow pattern. This was observed by replacing the side walls of low conductivity Plexiglas by thin glass walls. Inclusion of the side walls in the computational domain and solving the coupled fluid-solid heat conduction problem improved the agreement with the observed flow pattern. Also the observed temperature distribution as well as its symmetry were fully recovered in the numerical results (Fig. 21). It was only a result of use of *both* the experimental and numerical methods that the fine structures of the thermal flow were fully understood [33].



(a) (b) (c)

Fig. 20 Natural convection in the lid cooled cavities. Temperature distribution recorded with help of TLC directly under the cooled top wall. Effect of the walls properties on the flow structure visible in the temperature fields: (a) - plexiglass walls, (b) - glass walls, (c) - cylindrical glass cavity.



(a) (b) (c)

Fig. 21 Numerical results: temperature distribution under cooled lid for cube of plexiglass (low wall heat conductivity) - a, glass - b; azimuthal temperature distribution under the cooled lid for cylindrical cavity.

Interesting example of the temperature patter observed for the cylindrical cavity shows Fig. 20c. Despite cylindrical symmetry, the azimuthal flow structures appear, dividing the flow domain into regular sequence of 16-18 radial running rolls. Experimental evidence of this flow symmetry breaking was only possible with help of TLC visualisation method.

5. CONCLUSIONS

A new experimental technique, in this case true-colour image processing of liquid crystal patterns, allows new approaches to old problems and at the same time opens up new areas of research. Image processed data makes available quantitative, full-field information about the distribution of temperature and heat transfer coefficient which will undoubtedly encourage the study of situations which have been, until now, too complex to consider. The measuring technique comprising the use of LC flexible sheets and true-colour processing may also be used for a great variety of applications and should be of considerable use in aided analysis of colour images of unsealed TLC-tracers is a useful non-invasive method of investigating three-dimensional flow and temperature fields and their easy comparison with numerical results.

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