# Particle Image Velocimetry and Thermometry using Liquid Crystal Tracers

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**Abstract** There are only few techniques allowing an undisturbed and simultaneous monitoring of two important flow characteristics, i.e. temperature and velocity fields. One of such possibilities appeared when thermochromic liquid crystals became commercially available. Initiated almost 15 years ago technique of simultaneous measurement of temperature and velocity fields (Hiller & Kowalewski 1987) recently reached its mature state. In the following we describe our experience in applying the method to several problems studied in our laboratory. They include modeling flow configurations typical for the crystal growth problem, casting and boiling. The main aim of these experimental models is to generate reliable experimental database on velocity and temperature fields for specific flow. Then, such data can serve further validation of numerical codes before they are applied to technological or environmental problems.

## 1
## Introduction

Understanding of fluid flow with thermal effects is of great interest in a number of manufacturing and environmental problems. Progress in numerical techniques allows for simulation and modeling quite complex flow configurations involving thermal effects, also with phase change. Nevertheless, due to the problem complexity, direct application of numerical methods to many engineering problems is not a trivial task. Errors appear due to limited accuracy of different numerical methodologies and due to inevitable simplifications introduced in the models. Hence, the experimental verification of the models has gained special importance. However, there are only few techniques allowing an undisturbed and simultaneous monitoring of both flow characteristics, i.e. temperature and velocity fields. One of such possibilities gives seeding of the flow with thermochromic liquid crystals (TLCs). Small particles of the liquid crystal material suspended in the fluid ideally play a role of tracers following the flow pattern. Using standard PIV technique, the local velocity of the flow can be measured by cross-correlating two sequential images. In addition these particles change color with their temperature. Hence, after proper calibration, they behave as small thermometers simultaneously monitoring local fluid temperature.

Several studies have been made using TLC to measure flow velocity and temperature. However, due to the experimental difficulties most of them are limited to qualitative flow visualization experiments. Application of 3-CCD RGB camera and digital image analysis gave impact to develop the feasible concept of digital particle image thermometry (Dabiri and Garib 1991). Possibility to combine PIV and PIT was demonstrated by Hiller et al. (1993), who for the first time used the same suspension of TLC particles for digital evaluation of both temperature and velocity fields. Recently Park et al. (2001) documented in details PIV & T method applied to investigate turbulent flow. The uncertainty analysis given clarifies major limitations of the temperature calibration methods used by several authors. It follows that careful analysis of the acquired data is necessary to use the method for quantitative measurements of complex thermal and velocity fields.

In the following we describe application of the PIV & T method to experimental investigations of thermally driven flows such as natural convection in small cavities, solidification and boiling. The main aim of these experiments is to generate full field data on temperature and velocity fields, which can be directly compared with their numerical counterparts. We believe that despite of limited accuracy of the measurements, the non-intrusive character and possibility for instantaneous and full field measurements of velocity and temperature creates valuable extension to the traditional PIV technique.

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## 2
## Experimental technique

The temperature visualization is based on the property of some cholesteric and chiral-nematic liquid crystal materials to refract light of selected wavelength as a function of the temperature and viewing angle. Hence, at specific temperature range they appear as small color spots following the flow. Their color change ranges from clear at low temperature, through red as temperature increases and then to yellow, greens, blue, and finally clear again at the highest temperature. The color-temperature play interval depends on the TLCs 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 color changes are repeatable and reversible as long as the liquid crystals are not physically or chemically damaged. The response time of TLCs equals about 3ms. It is short enough for typical thermal problems in fluids.

In the experimental realization the investigated flow has to be illuminated by a light sheet. The arrangement is similar to that used for classical PIV experiments, however white light is necessary to obtain selected color refraction from the TLC particles. The color of light refracted by TLCs depends not only on temperature but also on the observation angle (Hiller et al. 1988). Therefore, it is important that the investigated flow is illuminated by well-defined light plane and observed by a camera from a fixed direction. To minimize color variation within the illumination plane the camera viewing angle should be kept small (less than 4° is advised). Any diffused or scattered light should be avoided as it modulates color of the light refracted from the TLCs.

Density of the TLC material is very closed to that of water and in most cases the TLC tracers can be treated as neutrally buoyant. The TLCs material can be commercially obtained as raw greasy mixtures or in the microencapsulated form. The encapsulated particles are chemically resistant and easy to use as tracers. However, the polymer shell used for encapsulation distorts the light and produces additional light scattering. Therefore in all our experiments we preferred to use TLC particles produced by dispersing the raw material in liquids. The major drawback of this approach is that in practice such particles were found to be chemically stable only in water and glycerol. Figure 1 demonstrates application of unencapsulated TLC tracers for visualization of natural convection in a cube cavity.

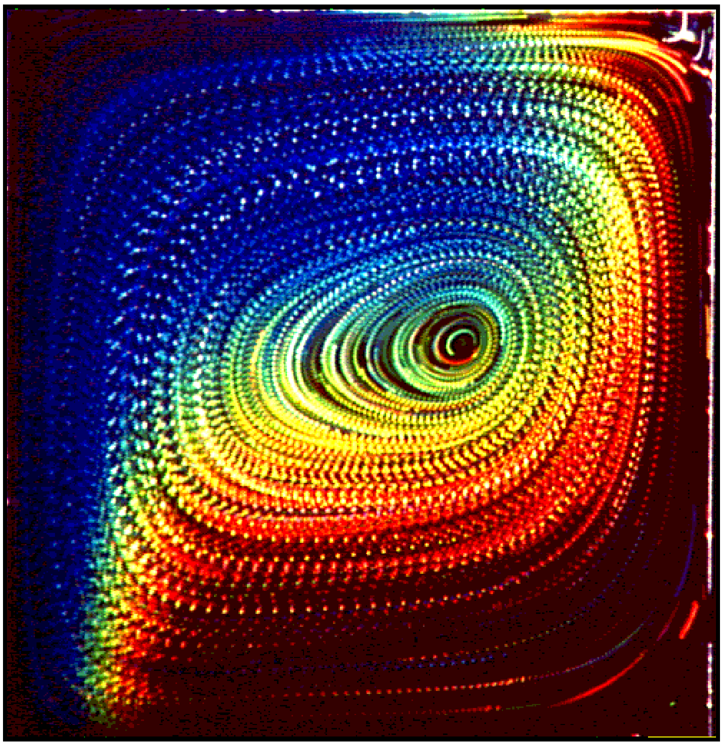


**Figure 1**. Multiexposed color photograph of the convective flow in glycerol seeded with liquid crystal tracers in a differentially heated cavity. Tracers change color from blue to red following the clock-wise flow circulation from the hot wall (left) to the cold wall (right); temperature difference $\Delta T=4^{\circ}C$.

The size of particles is another important issue. Large particles (0.1mm and more) produce strong, clear colors. As the size decreases, their color quickly faints due to the increasing effects of light scattering. Also the camera resolution starts to play an important role in color degradation, when particle images decreases to pixel dimensions of the sensor. Hence some compromise is necessary for optimal selection of the particle size. The mean diameter of the unencapsulated TLC tracers used in our experiments is usually about 50µm. Particles of such size guarantee bright, well visible colors of the refracted light and are still small enough to follow the flow. Smaller particles (10µm and less) were used for microscopic observations of the temperature field in the vicinity of a vapor bubble.

The temperature measurements are based on a digital color analysis of *RGB* images of the liquid crystals seeded flow field. For evaluating the temperature the *HSI* representation of the *RGB* color 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. Simple formulation introduced by Hiller et al (1993) is used to evaluate hue. The 8-bit representation of the hue value assures resolution better than 1%. However, the color - temperature relationship is strongly non-linear (comp. Fig. 2). Hence, the accuracy of the measured temperature depends on the color (hue) value, and varies from 3% to 10% of the full color play range. For the liquid crystals typically used it results in the absolute accuracy of 0.15$^{o}$C for lower temperatures (red-green color range) and 0.5$^{o}$C for higher temperatures (blue color range). The most sensitive region is the color transition from red to green and takes place for a temperature variation less then one Celsius degree.

Comparing to surface thermography (Hay & Hollingsworth 1996), the use of TLC as dilute suspension in a fluid bears additional problems. First of all, the color images of the flow are discrete, i.e. they represent a non-continuous cloud of points. Secondly, due to the camera properties, secondary light scattering, reflections from the sidewalls and internal cavity elements, the overall color response may be distorted. Hence, the use of specifically developed averaging, smoothing and interpolating techniques are indispensable to remove ambiguity in the resulting isotherms. Further, every experimental setup needs its own calibration curve obtained from the images using the same fluid, the same illumination, acquisition and evaluation conditions. This is a serious drawback of the PIT method. Whereas qualitative analysis of the temperature field can be relatively easy done, to obtain quantitative measurements additional support of few point measurements (e.g thermocouples) can make life much easier. It is because in general the shape of the calibration curve is a unique function of a whole acquisition and evaluation route used. Hence, often it is enough to estimate only its shift along abscissa to mach it with the actual calibration curve of a similar experiment done using the same setup (see also Hay & Hollingsworth 1996).

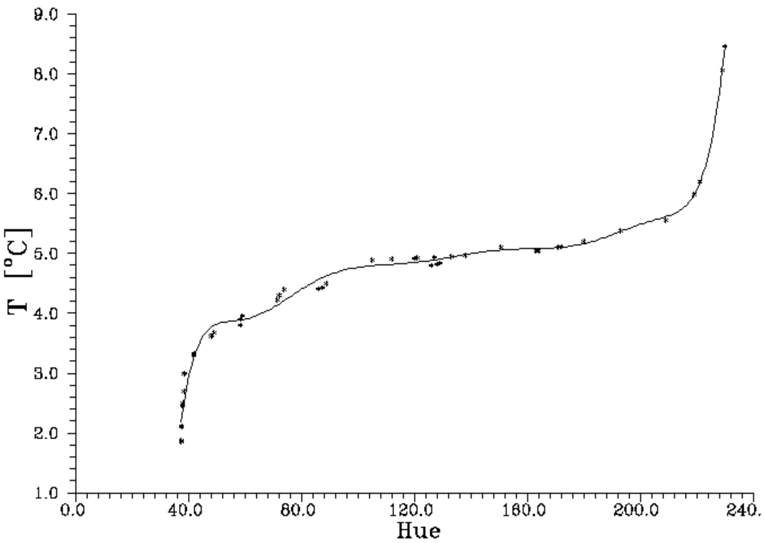



**Figure 2.** Temperature vs. hue for TLCs sample used to study natural convection of water with freezing. Calibration curve obtained by 8$^{th}$ order polynomial fitted to the experimental points

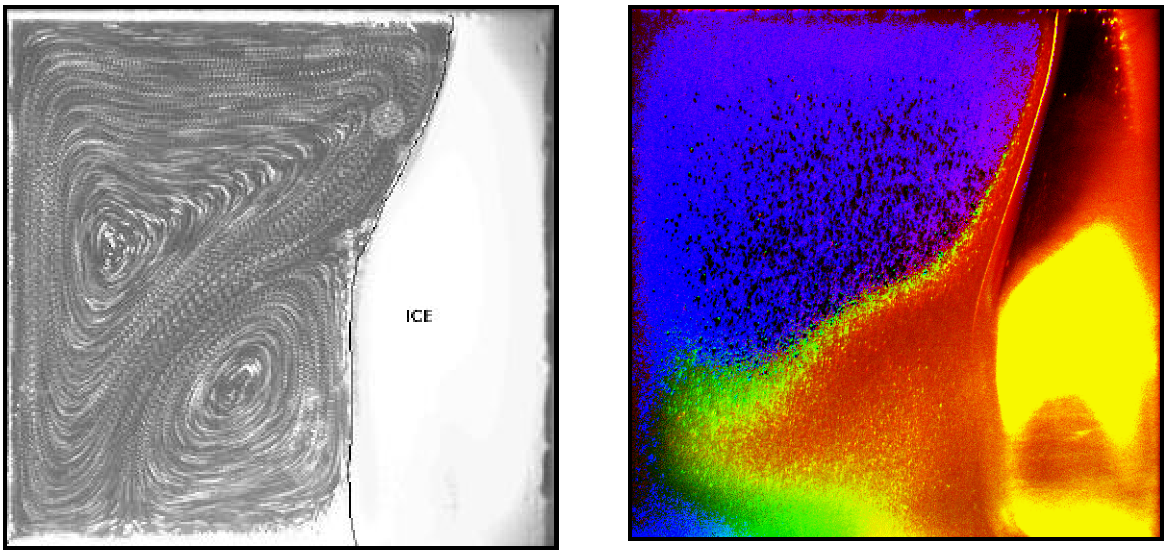
The full field velocity measurements are performed by particle image velocimetry (PIV) using the same color images. For this purpose, the color images of TLC tracers are transformed to B&W intensity images. After applying special filtering techniques bright images of the tracers, well suited for PIV, are obtained. One of the notorious drawbacks of the cross-correlation based PIV technique is relatively low signal dynamic for the velocity field obtained. It is mainly limited by a size of the correlation window and selected time interval between subsequent images. 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 simply changes time interval between two images. It allows us to preserve similar accuracy for both the low and high velocity flow regions. To improve resolution of the velocity field evaluation the recently developed ODP-PIV method (Quénot et al. 1998) of image analysis has been also used. Several accuracy tests performed for the artificial images have shown that for typical experimental conditions the 0.6 pixels accuracy of the „classical" FFT-based PIV could be improved to 0.15 pixels for the ODP-PIV method. It means that for typical displacement vector of 10 pixels the relative accuracy of the velocity measurement (for single point) is better than 6%.

In the typical experiment, the flow is illuminated by a xenon flash or a halogen lamp and observed at $90^o$ by a high resolution 3-CCD color camera. The 24-bit RGB images are acquired using a three-channel frame grabber and stored on a computer disk in digital form for further analysis. In the experiments described here we use PCI based 32-bit AM-STD module (ITI) and Pentium computer with 128MB memory. This setup permits us to get to the computer memory in real time over 50 RGB images of 768x564 pixels resolution, before they have to be saved on the disk. The system of step-motors combined with a mirror was used to acquire quickly images of several cross-sections of the convective flow in small cavities. Due to the relatively slow variation of the flow structures, transient recording of the main three-dimensional flow features was made possible. The computer controlling experiment drives stepping motors, triggers illumination and records the readings from control thermocouples. It allows for fully automatic recording of the transient velocity and temperature fields performed for several hours long experimental runs.

In the following we illustrate applications of the liquid crystal tracers for a few different cases of the thermally driven flow studied in the two configurations we explained before. In all these cases, the employment of TLCs appeared to be very useful in understanding the flow structure and helped us to discover effects, which are difficult to find using point measurements. Application of the digital image analysis allowed us to quantify measured temperature and velocity fields. Comparison with the numerical counterparts let us to identify discrepancies, which partly originated from the simplifications present in the numerical models.

## 3
## Solidification experiments

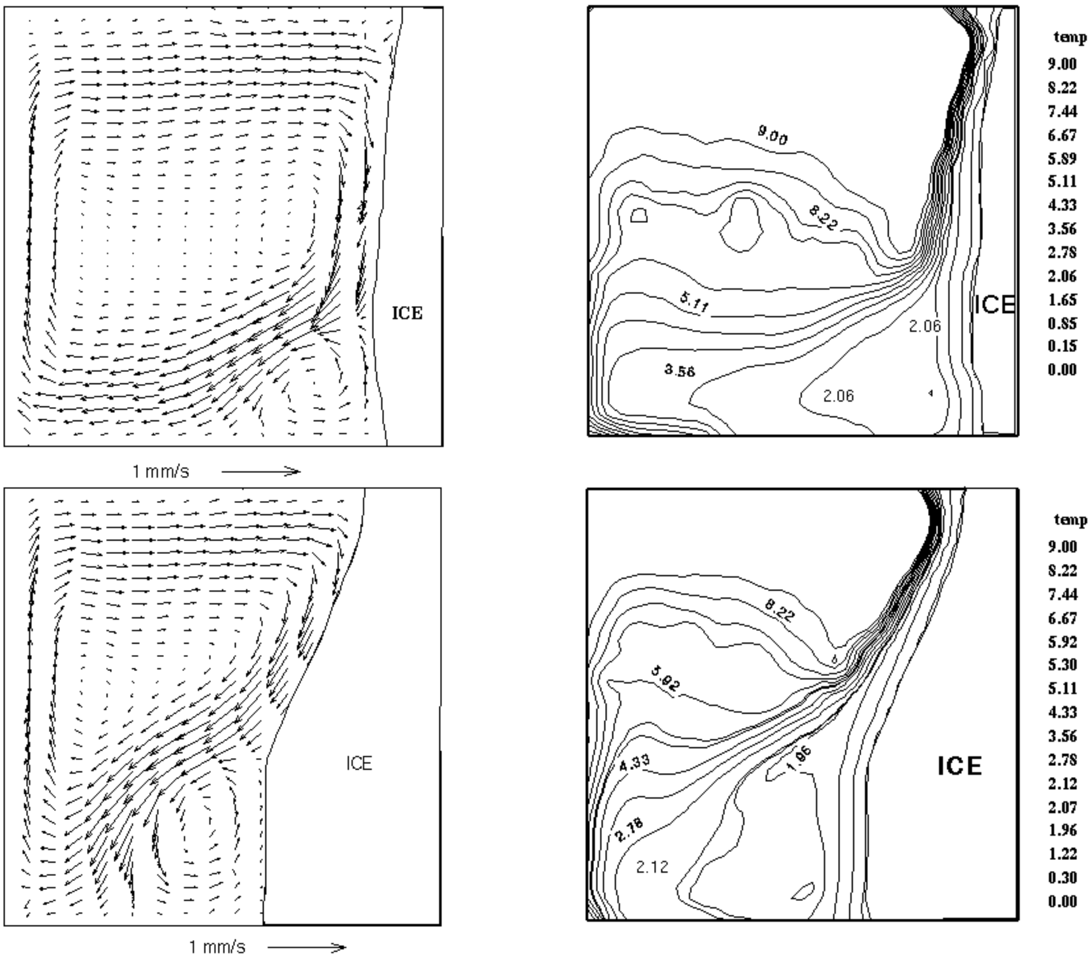
The behaviour of natural convection of water in the vicinity of the freezing point shows an interesting feature for the typical configuration with differentially heated walls. It is mainly due to the strongly non-linear temperature dependence of the density function with the extremum at $4^o$C. The competing effects of positive and negative buoyancy force result in a flow with two distinct circulations (Figs. 3). 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 counter-clockwise rotation (lower-right region). At the upper part of the cold wall the two circulations collide with each other, intensifying the heat transfer and effectively decreasing the interface growth. Below, the convective heat transfer from the hot wall is limited by the abnormal circulation, separating it from the freezing front. Hence, the phase front is only initially flat. As time passes it deforms strongly, getting a characteristic "belly" at its lower part.




a

b

**Figure 3**. Modeling directional solidification; water freezing in a differentially heated cube shaped cavity. Particle tracks showing flow structure (a), liquid crystals tracers indicating variation of temperature (b). Left hot isothermal wall at $T_h$=$10^o$C, right cold isothermal wall at $T_c$=$-10^o$C.



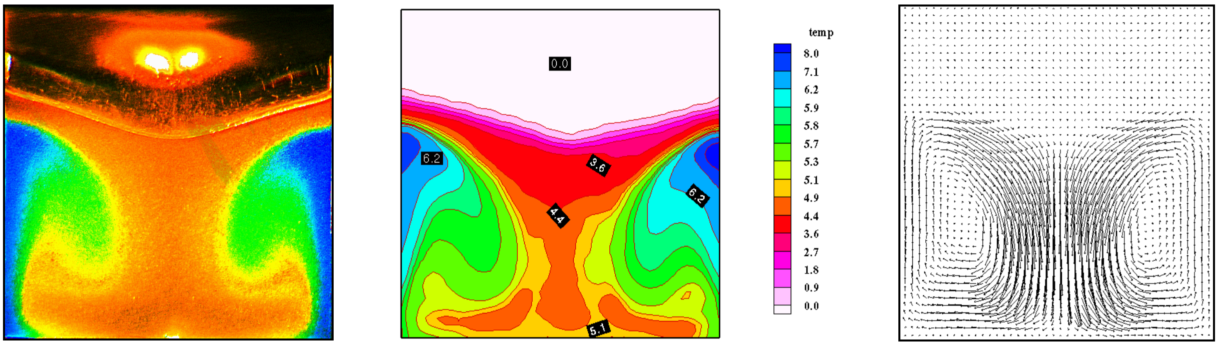

A b

**Figure 4.** PIV (a) and PIT (b) measured velocity and temperature fields for natural convection in center plane of differentially heated cavity at 500s (top) and 3000s (bottom). $T_h=10^oC$, $T_c=-10^oC$; $Ra=1.5 \cdot 10^6$, $Pr=13.3$

Digital analysis of the images seeded with liquid crystal tracers allows us to describe the full transient development of the temperature and velocity fields during the freezing process. Examples of the experimental results given here (Fig. 4) elucidate the complexity of the flow structure and its interaction with the thermal field. It is worth noting that the region separating the *normal* and *abnormal* circulations overlaps with the isotherms of the density maximum. Our numerical simulations performed for the freezing problem (Kowalewski & Rebow 1999) show severe discrepancies when compared with the experimental data. It comes out that this flow structure, with the two competing circulations, is very sensitive to thermal boundary conditions at the side walls. Neither isothermal nor constant heat flux models are sufficiently accurate to reproduce the observed flow structures. Full field flow measurements led us to discover main discrepancies and indicated directions to improve the model. Despite improvements of the numerical model we used, the computational results still differ in detail from their experimental counterparts. An eventual source of the observed discrepancies could be supercooling of water, which delays creation of the first ice layer and deforms the flow pattern at the top of the cavity. It is well known that pure water may supercool as far as $-40^oC$, before freezing occurs. Seeding of the flow with thermochromic liquid crystals allowed us to visualize that, in fact, initial water temperature reaches about $-7^oC$ before freezing starts.

In other investigated configuration, the top wall of the cavity is isothermal and kept at low temperature $T_c$. The other five walls are non-adiabatic, allowing a heat flux from the fluid surrounding the box. There is no well-defined "hot wall" in this configuration. The temperature at the internal surfaces of the cavity adjusts itself depending on both the flow and the heat flux through and along the walls. To define non-dimensional parameters describing flow, the external temperature $T_h$ is used to calculate the temperature difference. The lid-cooled 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, it resembles to some extent a directional solidification in a Bridgman furnace used for crystal growth.

Physically this configuration bears some similarity to the Rayleigh-Bénard problem. However, due to altered thermal boundary conditions at the sidewalls, the flow structure is different. For the cube shaped cavity as well as in the cylinder, 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. Numerical simulations confirmed this instability (Abegg et al. 1994). It appears that the initial cold thermal boundary layer at the lid is unstable and breaks down to several plumes falling down along the sidewalls. Depending on experimental disturbances or numerical noise present, the flow pattern exhibits several strongly asymmetrical transitions before a final configuration with a single cold "jet" along the cavity axis and a reverse flow along sidewalls establishes. A similar instability is observed by the onset of convection in the cylindrical cavity.



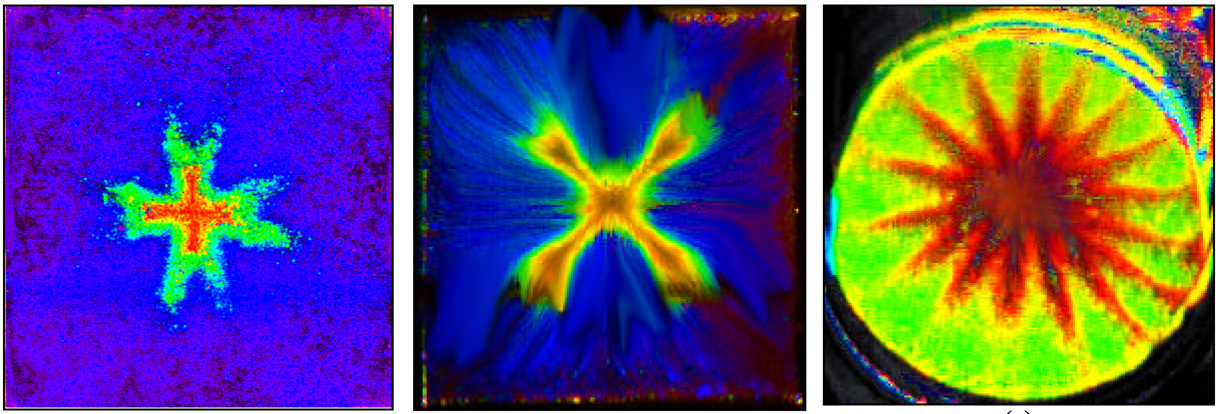

(a) (b) (c)

**Figure 5** Modeling crystal growth; 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; Isothermal lid temperature $T_c$= -10$^o$C, external bath temperature $T_{ext}$= 20$^o$C.

The formation of ice has been studied by decreasing the lid temperature down to **-**10$^o$C. A complicated flow pattern which establishes, becomes visible also in the structure of the ice surface. 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 ice solid surface, which imposes the direction and character of the flow, eliminating the instabilities observed in the pure convection case. There is also a density inversion under the lid, which decelerates the main "jet" and limits a strong generation of vorticity in that region.

Due to the stochastic development of the flow pattern, direct comparison of transient experimental and numerical results becomes difficult at early time steps. Hence, to minimize uncertainty of the initial conditions other arrangement was used. We call it the „warm start", because the freezing starts after a steady convection pattern is established in the cavity. This initial flow state corresponds to natural convection without phase change, with the lid temperature set to 0$^o$C. Regular flow pattern was seen, with the central, stable cold jet at the cavity axis. Figure 5 shows the temperature and velocity field evaluated at the time step 3600s for this case.

The flow visualization performed in the cube shaped cavity shows that the flow observed in the center plane, transporting fluid upwards along the side walls and downwards in a central cold jet along the cavity axis, in fact consists of the a complex spiraling structure in three-dimensions. Depending on the thermal boundary conditions at the sidewalls different configurations are realized by the flow. For walls of high heat conductivity (glass), eight symmetric cells are created by the flow. For Plexiglas walls, additional small recirculation regions appear, separating the main cells. The flow structure is also manifested in the complex structure of the ice surface. Both in the computed and observed ice surface, a star-like grooving reflects the eight-fold symmetry of the flow. A colour play of TLCs-seeded flow images taken directly under the lid (Fig. 6) shows differences of flow structures in the temperature pattern. It appears, that 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 with thin glass walls.

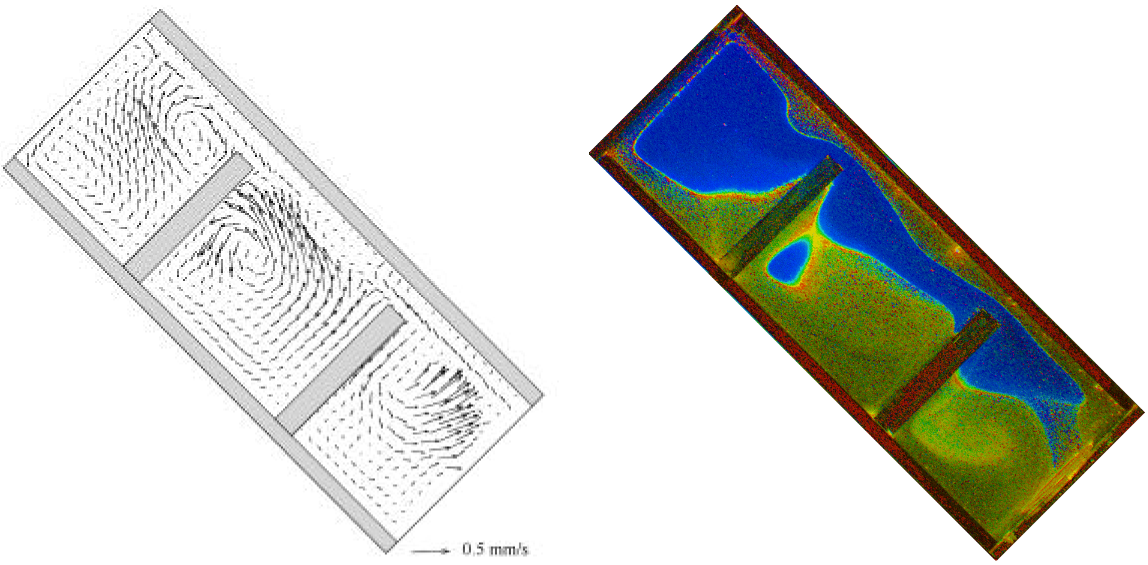


(a) (b) (c)

**Figure 6**. 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) - plexiglas walls, (b) - glass walls, (c) - cylindrical glass cavity

## 4
## Modeling casting problem

In this experiment a simple model simulating the main flow characteristics accompanying casting processes is investigated. The hot fluid is provided under high pressure into an inclined box. Fluid propagates inside the box between two cold isothermal walls, passing obstacles simulating internal complexity of a mould. The main features of the experiment like flow acceleration and deceleration on the obstacle, a free surface flow and sudden increase of the fluid viscosity as it cools down, are typical for a solidification of melt in a mould (comp. Fig.7). Opposite to a real casting, this experimental configuration allows for full control of the experimental conditions and the full field measurements of the temperature and velocity fields. Collection of the quantitative transient data of the flow should permit to verify and validate numerical models used for typical casting problems. The main aim of the investigations is to create an experimental benchmark for the mould-filling problem. To compare the experimental results, several numerical simulations of transient and steady states are performed. Our aim is to understand and explain the observed discrepancies between the measured and calculated flow patterns.




Velocity field (PIV) Temperature field (PIT)

**Figure 7.** Velocity field and temperature distribution visualized for the cavity inclined under 45°. Two cold isothermal walls (upper and lower) are responsible for sudden cooling of the fluid. It changes colour of the liquid crystals seeding from blue (hot) to red (cold regions).

## 4
## Vapor bubble growth

Modeling heat transfer during nucleate boiling is essential for many industrial processes. Despite a large number of studies devoted to this phenomenon during the last fifty years the problem is still far from being completed. In fact, numerous attempts have been undertaken to develop a general correlation for nucleate boiling heat transfer, but none has led to a satisfying result in a broad range of governing parameters. One of the still unsolved problems is the proper description of the process of formation, growth and detachment of a single vapor bubble. This fundamental problem for the boiling process phenomenon appears to be very difficult both for experimental investigations and for theoretical or numerical modeling. In the modeling of bubble detachment characteristics, a challenging thermodynamic problem must be solved. On the one hand, vapor bubble evolution involves complicated liquid and vapor flow against an unknown moving boundary. On the other hand, this flow is greatly influenced by at least three heat fluxes: from the bulk fluid around the bubble, from the hot solid surface through hypothecate liquid microlayer and from the vaporization at the interface. Heat transfer is, in turn, strongly affected by the flow. Solution of this complex, nonlinear problem appears intractable without drastic simplifications substantiated by empirical data. However, due to experimental difficulties most thermal and dynamic details concerning the growth and detachment of a single vapor bubble are rarely available.

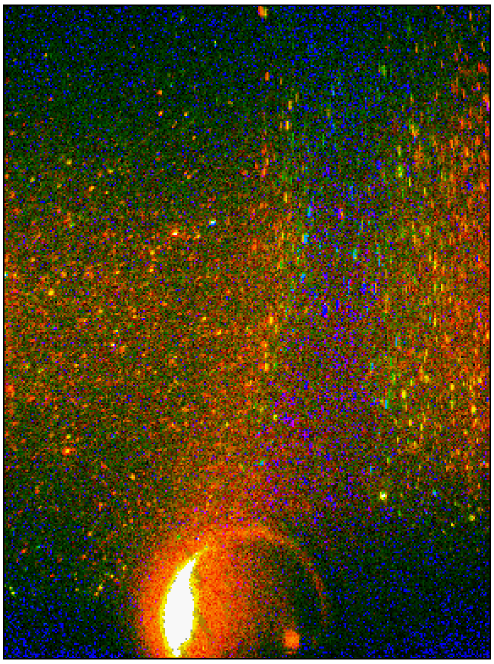
The microscopic observations supported by high-speed illumination system, CCD camera, and frame grabbers are used to obtain a quantitative description of the vapor bubble interface dynamics. Seeding of the fluid with thermochromic liquid crystals is used to visualize the temperature and velocity fields surrounding the bubble. The experiments were performed for water boiling in a low-pressure environment inside a small cube shaped cavity. The six walls of the cavity are equipped with several internal passages for water circulation from the thermostat. It allows for maintaining the cavity and the fluid inside at constant temperature within $\pm 0.1^oC$. In the experiments the bulk temperature of the liquid $T_l$ varies in the range $30^oC – 42^oC$.

The bubble and flow in the cavity can be observed through five glass windows. In the present experiment the bubble was observed through one of the side widows using a 3CCD-color camera (Kowalewski et al. 2000). To obtain images of a well-defined bubble interface back light illumination is applied using the opposite window. For this purpose both a strobe light and a halogen spot lamp are used. The second light source equipped with the halogen lamp is located perpendicularly to the optical axis of the camera. It is used to produce a 1mm light sheet for flow visualization around the bubble.

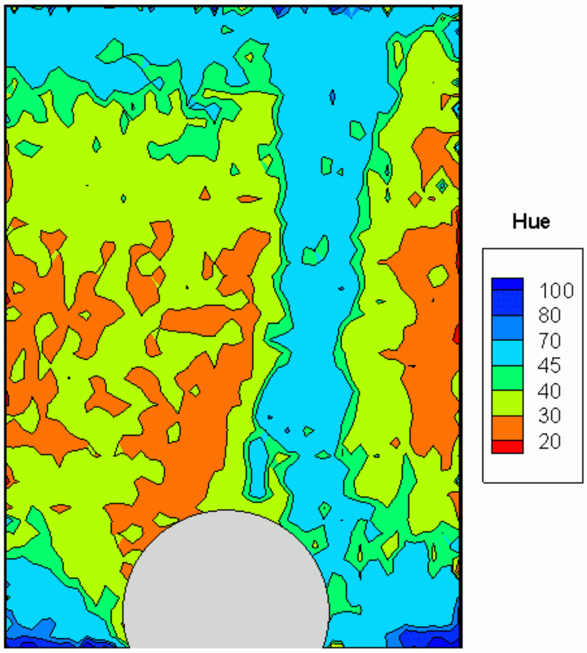
The bubbles are observed through a 50mm lens using an extension tube. A typical bubble diameter is about 2mm, and the mean velocity of the interface exceeds 0.1m/s. It means that the relative velocity in the plane of the CCD sensor is very high, requiring short illumination time and high-speed imaging. To obtain sharp images of the interface when a halogen light was used we applied the electronic shutter of the camera with a typical opening time 4ms. The strobe illumination from a standard stroboscopic lamp was used to study bubble dynamics.

The flow and temperature field surrounding the departing bubble appears to be very complex and difficult for analysis. The wide range of velocities, the sudden change of the flow direction, the generation of local vortices was typical for all our experiments. To separate the flow field induced by the growth of a bubble from the flow and temperature field generated in the cavity by natural convection, a sequence of images was taken, where the vapor bubble remains in a thermodynamic equilibrium. Under this condition, a flow in the cavity is driven by natural convection generated by temperature gradient between the heater and the bulk fluid. Figure 8 shows the original image with liquid crystal tracers, and results of its evaluation. A hot plum of fluid is visible as a blue stream emanating from the bubble surrounding. We may note that the presence of the bubble deforms the initial symmetry of the temperature and velocity field (Fig. 8b,c). Also the cold liquid sucked by the hot stream seems to very slightly affect surrounding of the bubble. It is well visualized by PIV evaluation of the flow field (Fig. 8c).

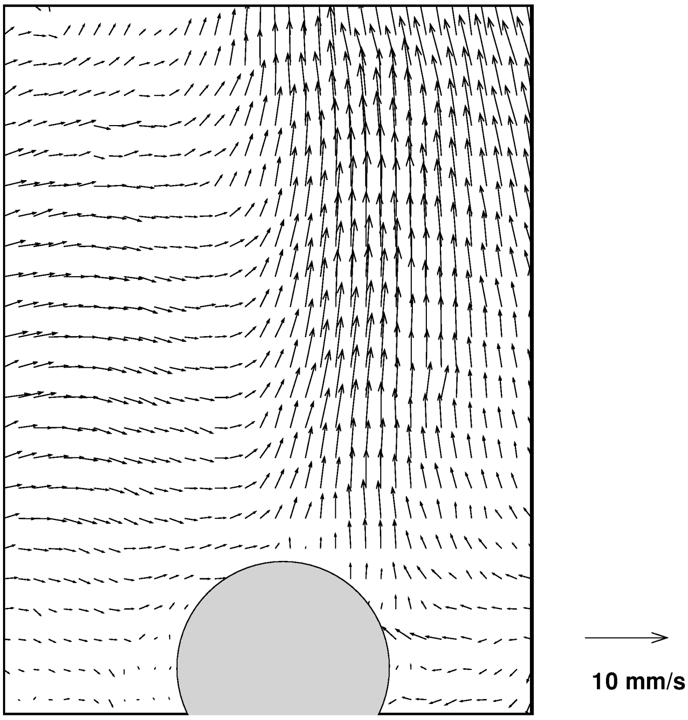
The main experimental problem with visualizing flow surrounding a growing bubble is due to strong light reflections from its surface. It noticeably diminishes resolution of the PIV and PIT evaluation in the vicinity of the bubble surface. One of the possibilities to minimize this effect is to mask part of the images obtained from the light sheet illumination by the second image of the bubble alone, obtained by backlight illumination. To acquire two separate images of the same object (backlight and light sheet illumination), we used two different colors. The blue filter was used for the light sheet and red LED diode was used for the backlight illumination. With RGB color camera, two different images were obtained for the red and blue channel, easy to use for the masking procedure. This technique was successfully applied to improve PIV evaluation of single bubbles. To preserve tracers color information, essential for PIT evaluation – a second B&W camera is necessary to create appropriate mask of the bubble.



(a) liquid crystal tracers




(b) evaluated isotherms (PIT)




(c) evaluated velocity field (PIV)

**Figure 8.** Flow field surrounding the steady vapor bubble visualized with liquid crystal tracers; evaluated temperature field (b) and velocity field (c); *P= 6.1kPa*, $T_l=35.7^oC$, $T_b=57^oC$

## 5
## Conclusions

An extension of PIV technique by using thermochromic liquid crystals as seeding opens new possibility in studying thermally driven flows. Image processed data makes available quantitative, full-field information about the temperature and velocity fields, which will undoubtedly encourage the study of situations which have been, until now, too complex to consider. The non-invasive character of the method and its relative simplicity offers valuable tool for the full field verification and validation of numerical results.

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