Particle Image Velocimetry and Thermometry for Two-Phase Flow Problems

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ABSTRACT: Image processing in fluid mechanics has become an important quantitative tool for flow analysis. The feasibility of simultaneous measurements of instantaneous velocity and temperature fields, as well as for tracking interfaces, creates a functional tool to describe thermally driven flows accompanied by phase change. The information thus gathered is essential for the verification and validation of computation models. The paper reviews the image processing methods developed by the author and his coworkers to analyze typical problems of two-phase flow. Simultaneous measurement of temperature and velocity fields, obtained by using liquid crystal tracers, are applied to elucidate solidification and growing vapor bubble problems.

KEYWORDS: particle image velocimetry; thermometry; liquid crystals; thermography

INTRODUCTION

Understanding fluid flow accompanied by thermal effects is of great interest in a number of manufacturing and environmental problems. Progress in numerical techniques allows the simulation and modeling of complex flow configurations involving thermal effects, including 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 various 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 that allow undisturbed and simultaneous monitoring of the relevant characteristics of the temperature and velocity fields. One such procedure consists of seeding 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 the standard particle image velocimetry (PIV) technique, the local velocity of the flow can be measured by cross-correlating two sequential images. In addition, these particles change color with temperature.[1] Hence, after proper calibration, they behave as small thermometers, simultaneously monitoring local fluid temperature.

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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. The application of 3-CCD RGB camera and digital image analysis gave impulse to developing the feasible concept of digital particle image thermometry.[2] The possibility to combine PIV and particle image thermometry (PIT) was demonstrated by Hiller *et al.,*[3] who first used the same suspension of TLC particles for digital evaluation of both temperature and velocity fields. Recently Park *et al.*[4] documented in detail the application of the joint PIV and PIT method to turbulent flow. Their uncertainty analysis clarifies the major limitations of the temperature calibration methods used by several authors. It follows that careful analysis of the acquired data is necessary when this method is used for quantitative measurements of complex thermal and velocity fields.

Here, we describe the application of the PIV and PIT 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 temperature and velocity data that can be directly compared with their numerical counterparts. We believe that despite of the limited accuracy of the measurements, the non-intrusive character and the possibility of instantaneous and full field measurements of velocity and temperature create a valuable extension to the traditional PIV technique.

EXPERIMENTAL METHODS

Temperature visualization is based on the property of some cholesteric and chiral-nematic liquid crystal materials to refract light of selected wavelengths as a function of the temperature and the viewing angle.[5] Hence, in specific temperature ranges 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, green, blue, and finally clear again at the highest temperature. These color changes are reproducible and reversible as long as the liquid crystals are not physically or chemically damaged.

A light sheet illuminates the investigated flow. The arrangement is similar to that used for classical PIV experiments. However, white light is necessary to obtain the selected color refraction from the TLC particles. Since the color of light refracted by TLCs depends on the temperature and the observation angle,[5] it is important that the investigated flow is illuminated by a 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.

The density of the TLC material is very close to that of water and, in most cases, the TLC tracers can be treated as neutrally buoyant. The size of particles is another important issue. Large particles (0.1 mm and more) produce strong, clear colors. As the size decreases, their color quickly fades due to the increasing effects of light scattering. Also, the camera resolution starts to play an important role in color degradation when the particle images approach the 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 was usually about 50µm. Particles of such size guarantee bright, easily 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 TLC material can be commercially obtained as raw greasy mixtures or in a 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, 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.

The temperature measurements are based on the digital color analysis of red, green, and blue (RGB) images of the liquid crystal seeded flow field. To evaluate the temperature, the incoming RGB video signals are transformed pixel by pixel into a hue, saturation and intensity (HSI) color map. The temperature is determined by relating the hue to a temperature calibration function. A simple formulation introduced by Hiller *et al.*[3] is used to evaluate hue with 8-bit resolution. However, the color–temperature relationship is strongly non-linear. 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°C for lower temperatures (red–green color range) and 0.5°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 1°C.

Compared to surface thermography,[6] the use of TLC as dilute suspension in a fluid bears additional problems. First, the color images of the flow are discrete—that is, they represent a non-continuous cloud of points. Second, the overall color response may be distorted due to the camera properties, secondary light scattering, and reflections from the sidewalls and internal cavity elements. Hence, the use of specifically developed averaging, smoothing, and interpolating techniques are indispensable to remove ambiguity in the resulting isotherms. Furthermore, 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 the qualitative analysis of the temperature field can be relatively easily done, additional support of a few point measurements (e.g., thermocouples) is necessary to obtain quantitative measurements.

The full field velocity measurements are performed by PIV using the same color images. For this purpose, the color images of TLC tracers are transformed to greyscale intensity images. After applying special filtering techniques, bright images of the tracers, well suited for PIV, are obtained. To improve the resolution of the velocity field, the recently developed optical flow based method of image analysis has also been used.[7] For a typical displacement vector of 10 pixels, the relative accuracy of the single point velocity measurement is better than 5%.

In a typical experiment, the flow is illuminated by a xenon flash or a halogen lamp and observed at 90° 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 a

PCI-based 32-bit AM-STD module (ITI) and a Pentium computer with 128 MB memory. This setup permits us to acquire in real time more than 50 RGB images with 768×564 pixel resolution, before they are saved on disk. A 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 possible.

The flow images were used to evaluate the shape and location of the phase front. These measurements were performed using image analysis software. As for the solidification front, the edge detection, supported by manual intervention, appeared to be the most efficient way to find the interfacial profiles. By integrating this information, the volumetric growth rate of the solid phase was evaluated. Concerning bubbles and droplets, a precise description of the interface is necessary for further analysis of their dynamics. Hence, to improve the accuracy, an additional high-speed backlight illumination was applied. The investigated objects were then recorded by a camera and appear as dark shadows, which are easy to detect and separate from the background. By selecting an appropriate edge detection routine, a sequence of pixels is extracted along the interface. In a second step, these pixels are used to find a functional representation of the bubble (or droplet) shape. This procedure allowed us to find a smooth description of the interface, necessary to evaluate its local velocity and curvature, and to evaluate the inner pressure.

The application of the liquid crystal tracers in a few cases investigated in our laboratory is illustrated here. The employment of TLCs seemed to be very useful in understanding the flow structure and helps us to discover effects that are difficult to find using point measurements. Application of the digital image analysis allowed us to quantify measured temperature and velocity fields. Furthermore, comparison with the numerical counterparts let us identify discrepancies that partly originated from the simplifications made in the numerical models.

INVESTIGATED CONFIGURATIONS

Solidification

We consider convective flow in a differentially heated cubic box. This configuration is often used as a benchmark for testing reliability of numerical solutions. In our case, two opposite vertical walls of the box are made of metal and assumed isothermal, the remaining four walls being made of plexiglas. One of the isothermal walls is held at temperature 10°C, the opposite wall is held at −10°C. The cavity inner size is 38 mm and it is filled with distilled water. The natural convection of water in the vicinity of the freezing point differs significantly from the well-known patterns of the benchmark solutions. The competing effects of positive and negative buoyancy forces result in a flow with two distinct circulations (see FIGURE 1). 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, intensifying the heat transfer and effectively decreasing the interface growth. Below, the abnormal circulation limits the convective heat transfer

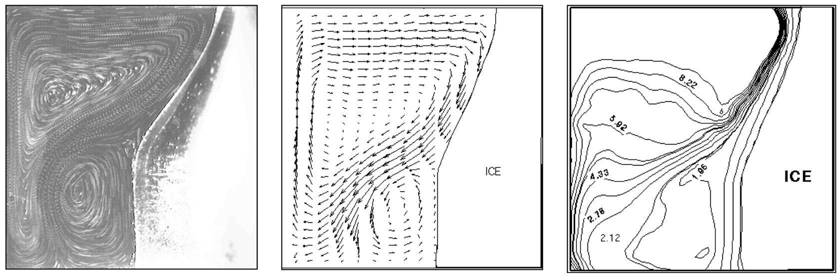

FIGURE 1. Modeling directional solidification; water freezing in a differentially heated cube shaped cavity with a hot isothermal wall (left) at $T_h = 10°C$ and a cold isothermal wall (right) at $T_c = -10°C$. **Left**, particle tracks; **center**, velocity field obtained by PIV evaluation of liquid crystal tracer displacements; **right**, variation of temperature evaluated from liquid crystals color.

from the hot wall, 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.

It is noteworthy 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[8] show severe discrepancies when compared with the experimental data. It turns out that this flow structure, with the two competing circulations, is very sensitive to the thermal boundary conditions at the sidewalls. Full field flow measurements led us to discover important discrepancies and indicated directions to improve the model. Despite of improvements in the numerical model we used, the computational results still differ in detail from their experimental counterparts.

In the second 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. In order to define the non-dimensional parameters describing the 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 the altered thermal boundary conditions at the sidewalls, the flow structure is different. The cubic symmetry of the enclosure imposes a strong downward flow along the vertical axis of symmetry. Several oscillatory changes in its pattern are observed before a stable final flow structure is achieved. Numerical simulations confirmed this instability.[9] 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 the experimental disturbances or the numerical noise present, the flow pattern exhibits several strongly asymmetric transitions before a final configuration with a single cold *jet* along the cavity axis and a reverse flow along sidewalls establishes.

The formation of ice was studied by decreasing the lid temperature to −10°C. The complicated flow pattern, which is established, also becomes visible 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 that decelerates the main *jet* and limits strong vortex generation in that region. Due to the stochastic development of the flow pattern, the direct comparison of transient experimental and numerical results is difficult in the early time steps. Hence, another arrangement was used to minimize the uncertainty of the initial conditions. 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°C. A regular flow pattern is then seen, with a central, stable cold jet at the cavity axis. FIGURE 2 shows the temperature and velocity field evaluated at time step 3,600 sec for this case.

To simulate the main flow characteristics accompanying casting processes, a simple experimental model was investigated using the PIV and PIT technique.[10] A hot fluid was injected under high pressure into an inclined rectangular box (38 × 38 × 110 mm) through a bottom inlet (see FIGURE 3 left). The fluid propagated inside the box between two cold isothermal walls, maintained at 10°C, passing two divisions simulating the internal complexity of a mould. Due to the sudden cooling of the fluid, the TLC tracers changed color from dark blue (hot) to red (cold regions).

The main features of the experiment (such as flow acceleration and deceleration at the obstacle, free surface flow, and sudden increase of the viscosity as the fluid cools down) are typical for the solidification of a melt in a mould. Moreover, contrary to a real casting, this experimental configuration allows for full control of the experimental conditions and for full field measurements of the temperature and velocity fields. The collection of the quantitative transient data of the flow should permit verification and validation of numerical models used for typical casting problems. The main goal of these investigations is to create an experimental benchmark

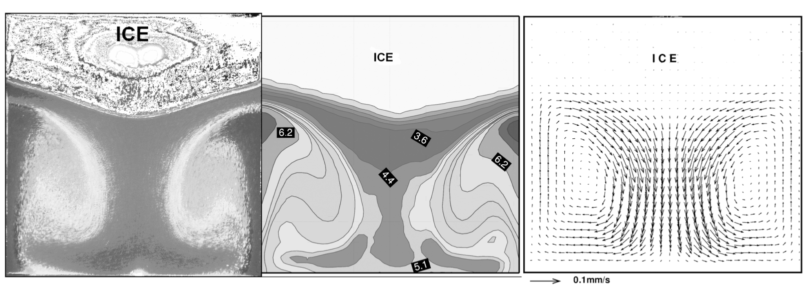

FIGURE 2. Modeling crystal growth: freezing of water from the top in the lid cooled cavity observed at 3,600 sec after cooling starts. Isothermal lid temperature $T_c = -10°C$, external bath temperature $T_{ext} = 20°C$. **Left**, recorded image of TLC tracers with central cold jet (dark color); **center**, PIT evaluated isotherms; **right**, PIV evaluated velocity field. (COLOR PLATE 6.)

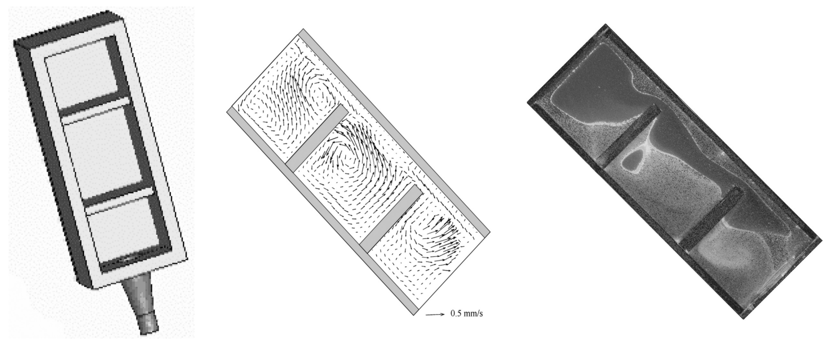

FIGURE 3. Cooling process observed just after filling the cavity with hot glycerol: **left**, geometry of the cavity with two partial divisions and flow inlet at the bottom; **center**, PIV evaluated velocity field; **right**, temperature field visualized by TLC. The cavity was inclined 45°, initial fluid temperature 50°C. Both isothermal walls (upper and lower) are kept at 10°C. Due to the sudden cooling of the fluid, the TLC tracers change color from dark blue (hot) to red (cold regions).

for the mould-filling problem. To compare with the experimental results, several numerical simulations of transient and steady states were performed. Our scope is to understand and explain the observed discrepancies between the measured and calculated flow patterns.

The solidification process of water, the working fluid, is observed as it sets in at both isothermal walls. Initially, almost uniformly and parallel to the wall, a layer of solid builds at both walls. However, as time progresses, the remaining effects of natural convection start to modify the heat transfer, resulting in a faster solidification at lower parts and an increase of asymmetry between upper and lower wall. The entire process depends on the inclination angle of the cavity. FIGURE 4 shows the experimental result obtained for water freezing in the cavity tilted at 11°. The initial water temperature was 9°C, the isothermal walls temperature −7°C.

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 past fifty years, the problem is still far from being resolved. In fact, numerous

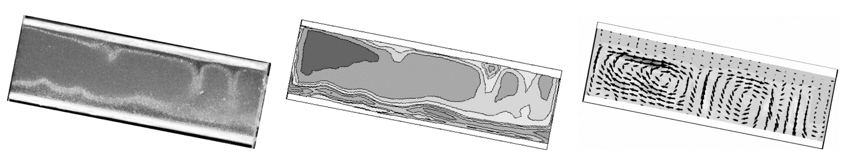

FIGURE 4. Solidification of water observed in the mould model without divisions. Ice layer at both isothermal walls 5 min after the filling process was finished: **left**, TLC tracer image; **center**, PIT evaluated isotherms; **right**, PIV evaluated velocity vectors and velocity magnitude contours. (COLOR PLATE 7.)

attempts have been undertaken to develop a general correlation for nucleate boiling heat transfer, but none has led to a satisfactory 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.

Microscopic observations supported by a high-speed illumination system, CCD camera, and frame grabbers were used to obtain a quantitative description of the vapor bubble interface dynamics. The 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. This allows us to maintain the cavity and the fluid inside at constant temperature (to within $\pm 0.1°C$). In the experiments the bulk temperature of the liquid T_l and the wall temperature T_b were varied over the range 30°C–70°C.

The bubbles and flow in the cavity could be observed through five glass windows. In the present experiment, a bubble was observed through one of the side windows using a 3CCD-color camera.[11] To obtain images of a well-defined bubble interface, back light illumination was applied using the opposite window. For this purpose, both a strobe light and a halogen spot lamp were used. The second light source, equipped with the halogen lamp, was located perpendicular to the optical axis of the camera. It was used to produce a 1 mm light sheet for flow visualization around the bubble.

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

The flow and temperature field surrounding the departing bubble turns out to be very complex and difficult to analyze. The wide range of velocities, the sudden change of the flow direction and the generation of local vortices were typical features of all our experiments. FIGURE 5 shows a vapor bubble departing from the hot surface. Liquid crystal tracers visualize the surrounding temperature and velocity fields.

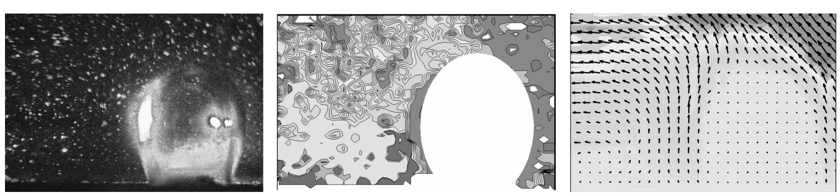

FIGURE 5. Flow field surrounding a departing vapor bubble. Water at $P = 5.3$ kPa, $T_l = 35.5°C$, $T_b = 66.5°C$. **Left**, TLC tracers; **center**, PIT evaluated temperature field; **right**, PIV evaluated velocity vectors and velocity magnitude contours. (COLOR PLATE 8.)

Within the surface layer they exhibit blue color, indicating an increase of temperature in the fluid. At the right side of the bubble, a relatively cold stream of water is visualized by the predominating red color of the TLCs. One can realize that the presence of the bubble strongly deforms the symmetry of the temperature and velocity field (FIG. 5 center and right).

The main experimental problem with visualizing the flow surrounding a growing bubble was due to strong light reflections from its surface. This noticeably diminished the resolution of the PIV and PIT evaluation in the vicinity of the bubble surface. One of the possibilities for minimizing this effect was 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. A blue filter was used for the light sheet and a red LED diode was used for the backlight illumination. With an 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 the PIV evaluation of single bubbles. To preserve the tracer color information, essential for the PIT evaluation, a second greyscale camera was necessary to create the appropriate mask for the bubble.

CONCLUSIONS

An extension of the PIV technique, by using thermochromic liquid crystals as seeding, opens a new possibility to study 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 that have been, until now, too complex to consider. The non-invasive character of the method and its relative simplicity offers a valuable tool for the full field verification and validation of numerical results.

ACKNOWLEDGMENTS

This is a summary of a study that I was fortunate to share with colleagues and students, first at the Max-Planck-Institut and presently at my home institution. In particular, I would like to acknowledge the contribution of W. Hiller, St. Koch, A. Cybulski, M. Rebow, and J. Pakleza (CNRS), to what has been a team effort over a number of years. The Polish Scientific Committee (KBN Grant No. 8T09A00820) partly supported this work.

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