PARTICLE IMAGE VELOCIMETRY AND THERMOMETRY FOR TWO-PHASE FLOW PROBLEMS

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Image processing in fluid mechanics became an important quantitative tool used for flow analysis. The feasibility of simultaneous measurements of instantaneous velocity and temperature fields, as well as tracking of the interface creates a functional tool to describe thermally driven flows accompanied by phase change. The full field information gathered becomes essential for verification and validation of the computational models. The paper presents a review of the image processing methods developed by the author and his co-workers to analyse a few typical problems of two-phase flow. Simultaneous measurements of temperature and velocity fields using liquid crystal tracers, as well as image analysis of the interface growth, are applied to solidification and growing vapour bubble problems. The shape analysis of images of oscillating droplets is used to obtain quantitative data about its surface properties. Following the experimental results, various aspects of their interaction with the numerical simulations will be discussed.

EXPERIMENTAL METHODS

The principle of the Particle Image Velocimetry (PIV) & Thermometry is based on seeding the flow medium with liquid crystal particles. The 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 thermochromic liquid crystals (TLCs) ranges from clear at ambient temperature, through red as temperature increases and then to yellow, greens, blue, and finally clear again at the highest temperature. The temperature measurements are based on a digital colour analysis of *RGB* images of the liquid crystals seeded flow field. For evaluating the temperature the *HSI* representation of the 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. However, the colour - temperature relationship is strongly non-linear. 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 liquid crystals typically used it results in the absolute accuracy of 0.15^oC for lower temperatures (red-green colour range) and 0.5^oC 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.

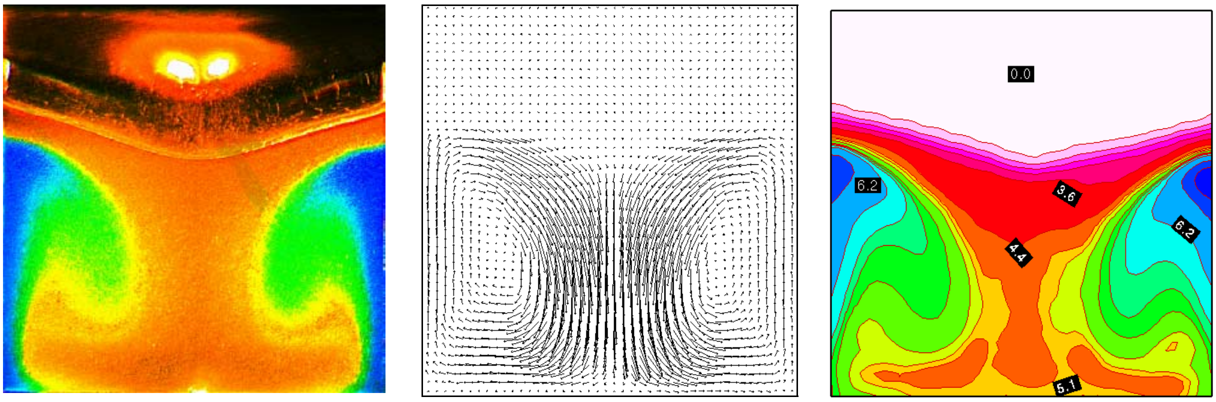
The full field velocity measurements are performed by PIV using the same colour images. For this purpose, the colour images of TLC tracers are transformed to B&W intensity images. After applying special filtering techniques bright images of the tracers, well suited for PIV, are obtained. One of the notorious 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 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 DPIV could be improved to 0.15 pixels for the ODP-PIV method[1]. It means that for typical displacement vector of 10 pixels the relative accuracy of the velocity measurement (for single point) is better than 6%.

The flow images are used to evaluate the shape and location of the phase front. These measurements are performed using image analysis software. For the solidification front the edge detection supported by a manual intervention appeared to be the most efficient way to find interface profiles. By integrating this information the volumetric growth rate of the solid phase is evaluated. For bubbles and droplets a precise description of the interface is intrinsic for further analysis of their dynamics. Hence, to improve the accuracy additional high speed backlight illumination was applied. Then the investigated objects recorded by a camera appear as dark shadows 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 the second step these pixels are used to find a functional representation of the bubble (or droplet) shape. This procedure allows us to find smooth description of the interface, necessary to evaluate its local deformation, velocity or inner pressure. For rather regular shapes observed for droplets the Legendre polynomials were used for the surface parameterisation. For complex deformations of vapour bubbles, the Bézier polynomials were found to permit us accurate and flexible shape description.

The typical experimental set-up used consists of a flow cavity, a halogen or Xenon flash lamp, the 3CCD colour camera and the 32-bit frame grabber (AM-STD-RGB ITI). The flow field is illuminated with a 2mm thin sheet of white light from a specially constructed collimator, and observed in the perpendicular direction. When the backlight illumination is necessary to study bubbles dynamics an additional short pulse of light from LED was used. About hundred 24-bit colour images of 768x564 pixels can be acquired in real time using a 128MB Pentium III computer. The mean diameter of the unencapsulated TLC tracers we use is in the range of 10-50μm, the volume concentration is well below 0.1%. Their effect on the flow can be neglected. Full 2-D temperature and velocity fields are determined from a pair of colour images taken for the selected cross-section of the flow. Furthermore, a 3-D flow structure can be reconstructed from several sequential measurements, if the flow relaxation time is sufficiently long.

INVESTIGATED CONFIGURATIONS

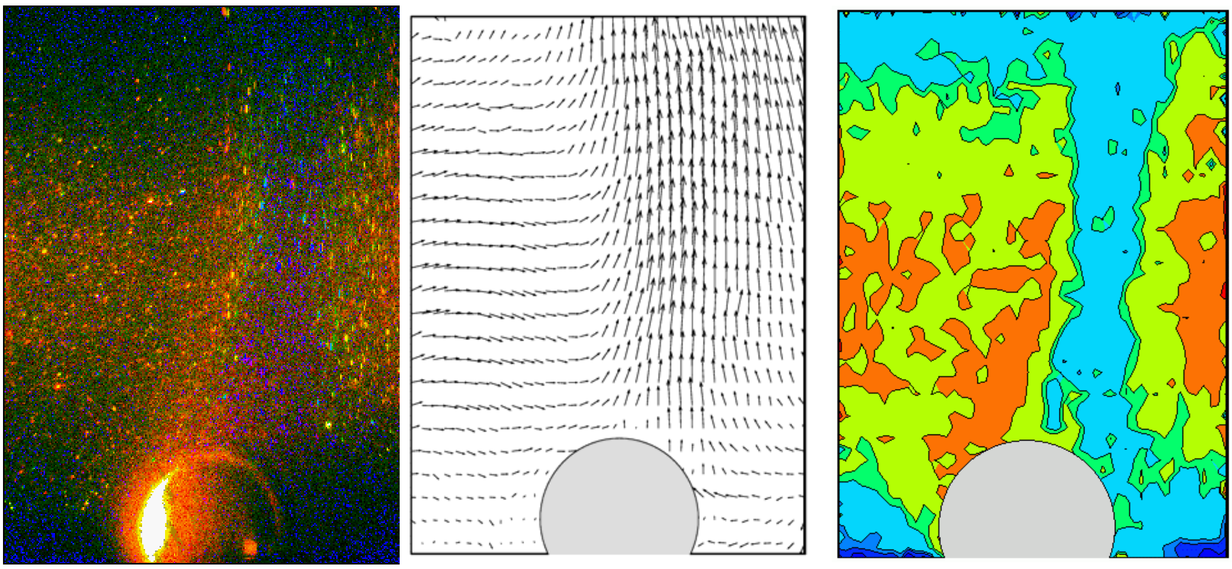
The onset of convection with solidification in transparent cube shaped and cylindrical cavities was investigated using the PIV&T method[2,3]. Water freezing under horizontal and vertical temperature gradient was used to simulate configurations typical for a directional crystal growth in a Bridgman furnace. Flow visualization and image analysis performed allowed us to find complex flow structures developed in the cavity. For the horizontal configuration the phase front is only initially flat, with time becomes strongly deformed, with a characteristic "belly" at its lower part. For the vertical configuration a three-dimensional flow structures dividing the flow domain are responsible for the characteristic grooving of the conical interface. Interesting azimuthal structures are observed for the vertical cylinder. The temperature and velocity fields together with the interface geometry can be directly compared with their numerical counterparts, allowing detailed verification of computational models used.



(a) (b) (c)

Fig. 1. Freezing of water from the top in the lid cooled plexiglas cavity. Colour image of liquid crystal tracers (a), evaluated velocity (b) and (c) temperature fields.

Modelling heat transfer during nucleate boiling is still far from being completed. The fundamental problem for this process, i.e. growth and detachment of a single vapour bubble, was studied for water boiling under low-pressure conditions. The PIV&T was applied to obtain transient development of the velocity and temperature of the surrounding liquid[4,5]. The flow and temperature field surrounding the departing bubble appears to be very complex. The wide range of velocities, the sudden change of the flow direction, the generation of local vorticies were typical for all our experiments. The tracer-less PIV evaluation scheme was applied to the bubble images to obtain local velocity of the interface. The edge detection procedure allowed us to resolve location of the contour and to evaluate the local curvature and both, the tangential and the normal components of the interface velocity, data very important for constructing evaporation models.



(a) (b) (c)

Fig. 2. PIV&T applied to evaluate velocity and temperature field surrounding the vapour bubble in water: a- colour image of tracers, b- velocity field, c- isotherms.

Understanding physics of the droplet evaporation is essential for a number of important technical processes. The evaporation process is directly related to the surface temperature of the droplet, the parameter difficult to measure by classical means. If the droplet oscillates the oscillation frequency can be related to the surface tension, parameter depending on the surface temperature. Hence, in our experiments image processing is applied to study oscillations of alcohol droplets moving in the air[6]. The LED illuminated droplets were acquired under a microscope using a CCD camera and frame grabber. The images of the free oscillating droplets are used to evaluate the instantaneous value of surface tension, hence eventually the surface temperature as well. The transient data on the droplet surface deformation is used to verify numerical simulation of the phenomena.

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Additional images and references can be found at the Web page: http://www.ippt.gov.pl/~tkowale/