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Non-Isothermal Flow Diagnostics Using Microencapsulated Cholesteric Particles

GÜNTER WOZNIAK*
Lehrstuhl für Experimentelle Mechanik, Technische Universität Bergakademie Freiberg, Lampadiusstraße 2, D-09596 Freiberg, Germany

KLAUS WOZNIAK and JULIUS SIEKMANN
Fachbereich 12 – Mechanik, Universität-GH Essen, Schützenbahn 70, D-45117 Essen, Germany

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Abstract. The temperature and the flow field of thermo-convective liquid flows are visualized using cholesteric liquid crystal material as tracer particles. This type of tracers offers the scientifically valuable feature of measuring the flow and the temperature field simultaneously. Three thermo-convective flow configurations have been investigated successfully using liquid crystals. The results are discussed in some detail. It turns out that the liquid crystal technique is a valuable tool for thermo-convective liquid flow analysis.

Key words: liquid crystals, buoyant and thermocapillary convection, flow visualization

Introduction

In numerous experimental studies regarding the momentum, heat and mass transfer of thermal liquid convections, optical methods have been applied to capture the flow and the temperature field, respectively. For example, in order to measure the temperature distribution within these flows, interferometry has been used frequently [1]. The flow velocity field very often has been measured by employing laser-Doppler-velocimetry (LDV) or particle-image-velocimetry (PIV) [2]. A novel technique is the use of liquid crystals as tracer particles. They offer the feature of reflecting a selective colour depending on their temperature when illuminated with white light. Hence, it is possible to capture simultaneously the flow field by tracking of the particles and the temperature field by detecting the particles' colour. Nozaki et al. [3], for example, applied liquid crystals to study remotely the heat transfer in liquid drops.

For many industrial processes the knowledge of the behaviour of liquids due to temperature gradients in the fluid is of fundamental importance. On earth, temperature gradients cause fluid density variations, which in turn lead to flows driven by buoyancy forces. However, in orbit buoyancy effects vanish due to the absence of gravity. In this situation fluid motion can be caused by a free surface or interface

* Author for correspondence.

between immiscible liquids. This fluid motion is a consequence of the variation of the surface tension or interfacial tension with temperature and is called thermocapillary convection. While this effect is often masked by buoyant effects on earth, it can play a dominant role under reduced gravity conditions. Present activity areas in space processing are the production of two-phase materials using the absence of sedimentation, the containerless processing of glass to obtain a better product quality, and the growth of larger single crystals exhibiting higher purities when compared to crystals grown on earth. Also bubbles, resulting from solidification, melting and other operations present surfaces which can cause thermocapillary convection. Furthermore, bubbles are serious defects in crystals [4]. Both buoyant and thermocapillary flows are commonly referred to as thermo-convective flows.

The objective of the present study is the demonstration and application of a measuring technique being capable of capturing the velocity and temperature field of a selected flow plane simultaneously, and its application to three typical thermo-convective flow configurations:

(i) Bénard convection in a rectangular cavity heated from below and cooled from above (unstable stratification),
(ii) thermocapillary flow driven by bubbles under a heated wall,
(iii) thermo-convective flow of a double layer fluid system.

Flow Configurations

Figure 1 shows schematically the flow configurations under investigation. Flow (i) is the so-called Bénard convection resulting from an unstable thermal liquid stratification. The liquid layer of height h is heated from below (temperature T_1). The vertical temperature difference was $\Delta T = T_1 - T_2 = 1.2$°C, where T_2 ($< T_1$) denotes the temperature of the upper boundary of the test cell. Due to the aspect ratio of the fluid layer of 10 : 4 : 1 (length 60 mm × width 24 mm × height 6 mm) ten convective vortices appear. This flow is stationary but becomes transient by increasing the temperature difference. The second arrangement (ii) is a surface tension driven flow of air bubbles in silicone oil exhibiting an upward vertical temperature gradient. The convection is directed toward the coldest location of the bubble surface, that is, the bubble pole exhibiting the highest surface tension. The resulting toroidal vortex ring is a result of the interaction between surface tension and buoyancy driven motion. Configuration (iii) consists of a horizontal double layer of two immiscible liquids. Here, a horizontal temperature gradient has been applied by heating the fluid cell from the right and cooling it from the left. This leads to variations of the interfacial and surface tension, respectively. As a result, a flow due to thermocapillary and buoyancy effects has been established in the experiments. The double layer configuration has been suggested as a means to suppress the thermocapillary flow of a liquid column in crystal growth. The lower liquid represents the melt, whereas the upper liquid models the encapsulating material. The motivation of taking this measure is the lower variation of interfacial tension

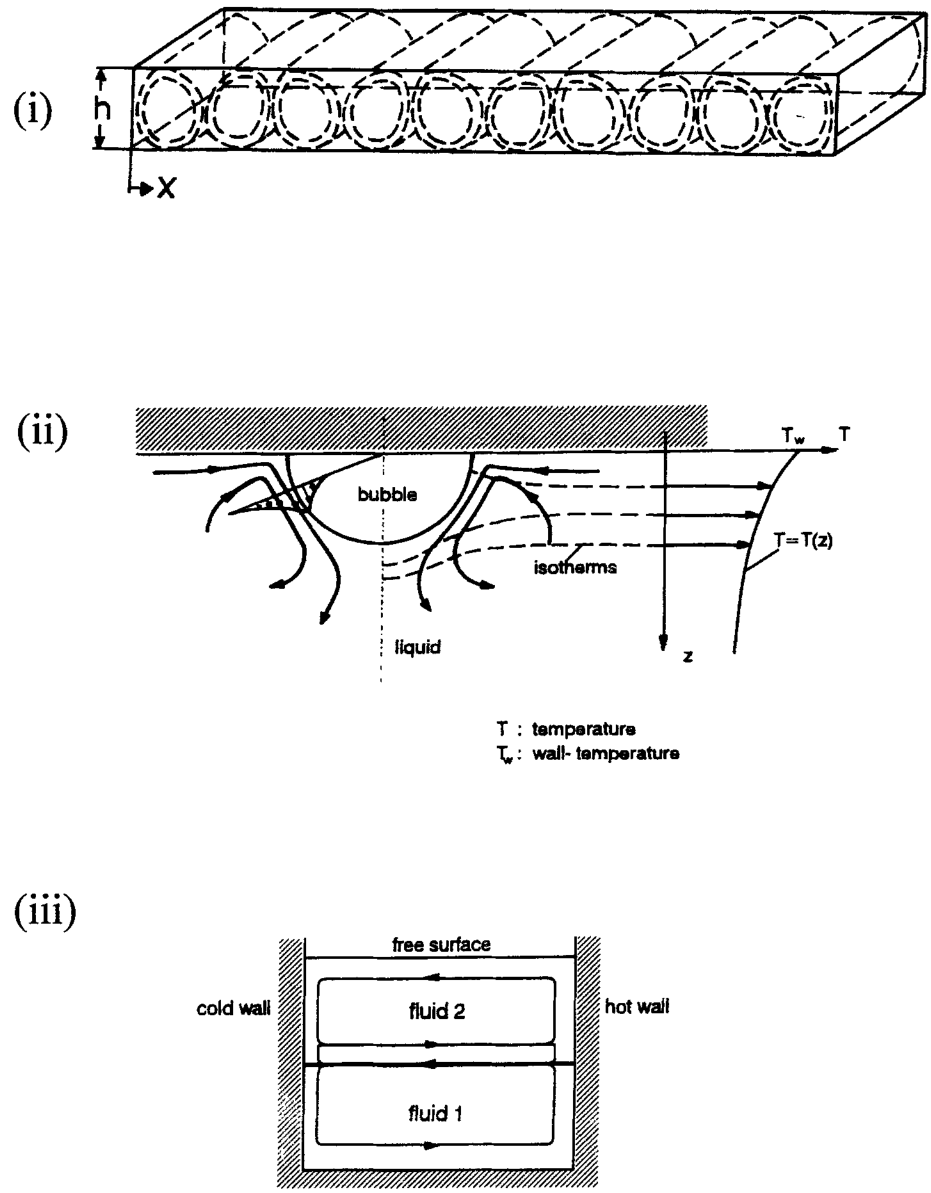

Figure 1. Schematics of the investigated flow configurations: (i) Bénard convection; (ii) Thermocapillary convection of a bubble; (iii) Thermo-convective flow of a fluid double layer.

with temperature of certain liquid/liquid systems, when compared to variations of the surface tension with temperature of liquid/gas surfaces.

Experimental

HARDWARE AND TEST FLUIDS

The heart of the experimental set up is the test cell containing the relevant flow configuration. The three experiments have been conducted with different cells each equipped with Peltier elements, resistance heaters or a cavity for circulating cooling water in order to establish the temperature gradient. In the Bénard experiment for example, the interior of the cavity is heated and cooled by copper plates being the horizontal cavity boundaries. The fluid volume is closed by a frame of optical glass for visualization purposes. The test cells of the configuration (ii) and (iii) are constructed in a similar manner. For flow visualization we applied a sheet of white light with a thickness of approximately 1 mm. As light source served a Xenon-arc lamp, the beam of which was shaped by a suitable lens system. The test fluid of the Bénard experiment was water. The air bubble experiment was performed with silicone oil of 10 centistokes nominal viscosity as working liquid. In the double layer experiment fluid 1 consists of a 50% water/glycerine solution exhibiting a nominal viscosity of 5 centistokes, while fluid 2 is a silicone oil of 10 centistokes nominal viscosity. Since the three flow configurations are two-dimensional (i) and (iii), or axisymmetric (ii), light sheet illumination is sufficient to catch the complete flow information.

LIQUID CRYSTAL TECHNIQUE

As outlined before, the principle of the method is based on seeding the liquid flow medium with liquid crystal particles which are able to indicate both the velocity- and the temperature field. The investigated flow plane is illuminated by a light sheet and recorded on photographic material via multi-exposures. The resulting flow image contains the tracks of the particles and thus the spatial velocity information within the plane of the light sheet. In addition, the respective colours of the particles indicate the local temperature within the illuminated plane and thus the temperature field.

Chiral nematic liquid crystals behave as multilayered Fabry–Perot interference filters and reflect incident visible radiation selectively. Any disturbance of the forces maintaining the internal structure of the crystals results in a change in the wavelength of the selective reflection. If the variation of the distance of the internal interference layers is due to temperature changes, the selectively reflected colour of the crystal is a measure of the temperature. This process is reversible and can therefore be used for temperature measurements provided the crystals are properly calibrated. This has been done by applying the crystals in an isothermal bath, illuminating them with the same optics as in the flow experiments and recording the reflected colours as a function of temperature on photographic material. In this respect it should be noted that the shear-stress dependences of the colour reflection behaviour of the liquid crystals are eliminated in this study as a result of their

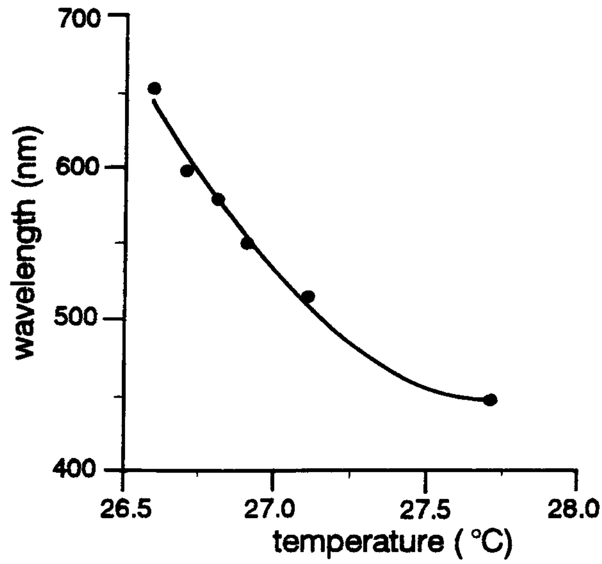

Figure 2. Reflected wavelength of the applied liquid crystal TTC 1001 *versus* temperature.

encapsulation with some resins. Details of the physics of liquid crystals can be found, for example, in [5]. Since the reflected colour play of the crystals is also depending on the viewing angle, we adjusted the angle between the illumination and the recording axes in the calibration experiments as well as in the flow experiments to 90°. The evaluation of the coloured flow images was then performed by human inspection and comparison between calibration and flow images. In the described experiments we used encapsulated liquid crystal tracers of about 12 μm in diameter (type TCC 1001, BHD Chemical Ltd.). The concentration of the crystals within the flow liquid was approximately 0.1 weight percent. When illuminated with white light, this type of liquid crystal material reflects light with a wavelength according to the calibration curve shown in Figure 2. Liquid crystals have a temperature response time of 50 ms and are available at working temperatures between −30 and 200°C. Colour play intervals available today lie between 0.5 and 60°C. The density of the liquid crystal tracers is approximately 1003 kg/m^3 and thus close to the one of the working fluid. We conducted sedimentation tests and found that sedimentation becomes only visible after several days. Consequently, we neglected this effect.

In order to check the sensitivity of the surface tension and its variation with temperature of the pure test fluids to liquid crystal seeding we have measured their surface tension with and without the presence of the tracers using the Du Noüy ring method. Since we did not measure any significant deviation, we neglected this effect during the thermocapillary experiments as well.

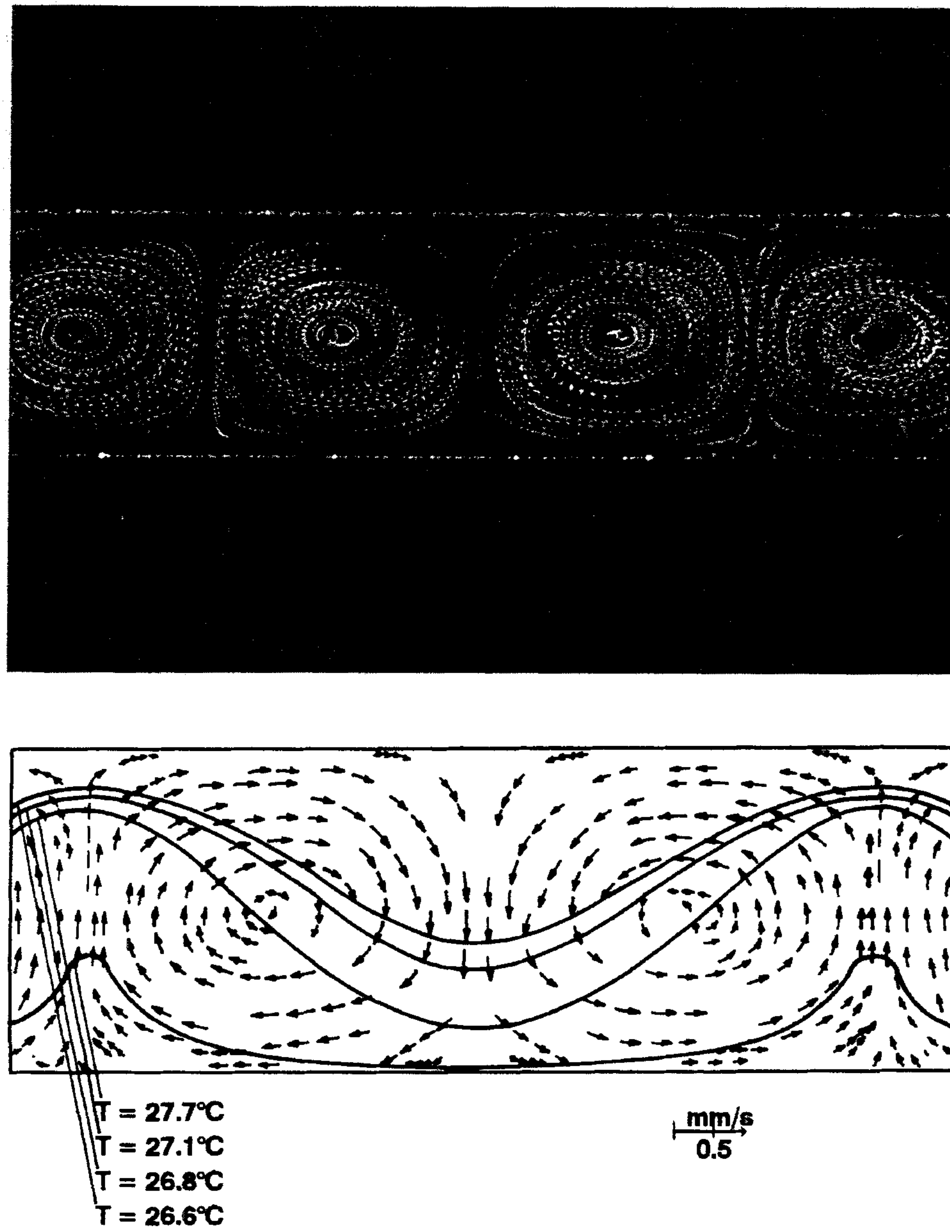

Figure 3. Results of the Bénard experiment (i), Ra = 4000. Note the reference vector at the right bottom of the velocity plot.

Results and Discussion

CONFIGURATION (I)

Figure 3 shows the colour image of the Bénard experiment and its evaluated data. The value of the well-known Rayleigh number, comparing the relative importance of buoyant forces to viscous forces is Ra = 4000. Ten convection rolls developed at a selected cavity aspect ratio 10 : 4 : 1. Figure 3 displays the liquid crystal tracer image of the magnified four left rolls. The wavy outline of the thermochromatics indicates the location of the isotherms. The velocity distribution of this configuration has been evaluated by particle-image-velocimetry out of the image negative. Details are given in the following and are further described in [2]. The acquisition technique for flow fields bases on the record (in our case photographic image of the particles on a negative) of particle reflections within the flow. With the help of a suitable optical system a thin light sheet is shaped to illuminate a vertical flow plane. When the time interval between the exposures is matched to the fluid velocity, the tracers will move a few diameters without loosing their identity (in our experiments the time between two exposures was one second). Various local displacements in the illuminated flow field provide characteristic patterns of particle ensembles with variable distance and orientation. The velocity field information is stored on photographic material and can be reconstructed by a method explained in the following. The so-called pointwise interrogation technique was employed to evaluate the multiexposed negatives. For that a thin laser beam traverses a multiexposed negative at a certain point of the flow image. Particle images act like point sources, which emit light into the ambient. The superimposed wavelets of each particle image interfere and cause parallel equidistant interference fringes visualized on a screen. The fringes are perpendicular to the direction of the particle displacement. Measuring the fringe spacing and orientation leads to the local velocity vector of the flow. The resulting interference patterns are evaluated using digital image processing techniques including the 2-D fast Fourier transform. A detailed description of the computational procedure is published in [6]. A point by point evaluation of the negative eventually leads to the velocity field.

Regarding the image recording and processing the first step is to produce a double- or multiexposed colour image of the illuminated flow plane containing the particle tracks and the colour distribution of the cholesteric particles. The colour distribution reveals the location of the isotherms. The next step is to transform the chromatic image (colour negative) onto monochromatic film material. This transformation causes a strong increase of the contrast between the particle images and the background which means an improvement of the particle image quality. The transformed film material may now be used to reconstruct the velocity field. By way of this procedure the velocity (PIV) and temperature distribution are available, both captured simultaneously.

In order to test our method regarding the velocity measurements we compared our PIV-data with two-dimensional numerical predictions by Oertel [7]. Figure 4 displays scaled vertical velocities u_v of the horizontal midplane of the Bénard configuration. In the course of our investigations we also used a laser-Doppler-velocimeter (LDV) featuring an integrated Bragg cell. The superposed LDV and PIV data reveal satisfying agreement with data of the numerical model. The uncertainty of our measurements turned out to be less than 5%. Furthermore, the experi-

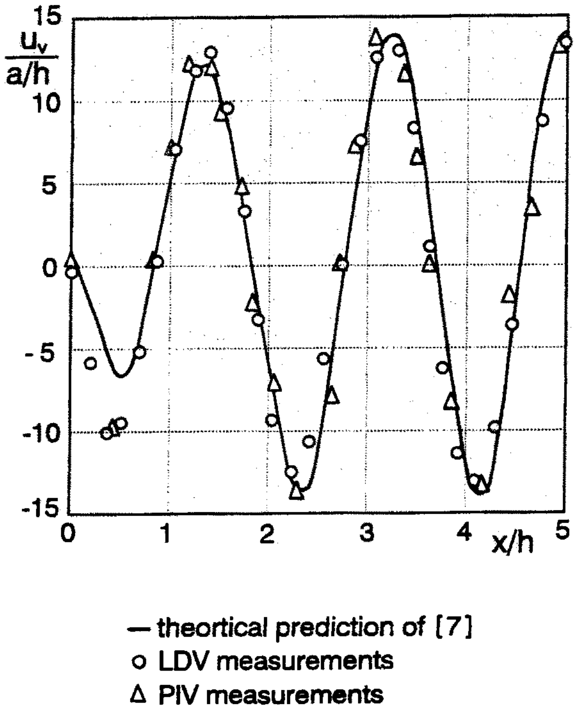

Figure 4. PIV results and comparison with reference data. The vertical velocity profile (of the horizontal midplane) is scaled with the thermal diffusivity a of the liquid and its layer height h, x is the horizontal coordinate indicated in Figure 1(i).

mentally observed vertical velocity data show stronger deviations from theoretical results near the vertical side walls. A major reason for these velocity deviations are the simplified and idealized boundary conditions of Oertel's theoretical model. The assumption that the material data are temperature independent causes some additional uncertainties when comparing model and experiment. Four isotherms resulting from the colour play of the liquid crystals are superposed on the velocity distribution. The colours blue (447 nm), green (514 nm), yellow (585 nm) and red (648 nm) indicate four isotherms. A further colour evaluation with increased resolution would require the application of digital image processing techniques capable of determining two-dimensional temperature distributions automatically [8].

CONFIGURATION (II)

Figure 5 displays the multiexposed colour image of the thermocapillary bubble experiment. Two air bubbles of 5 mm maximal horizontal dimension under a heated wall are subject to an upward vertical temperature gradient. The applied temperature gradient in the undisturbed liquid stratification was about 1.56 K/cm. Each bubble

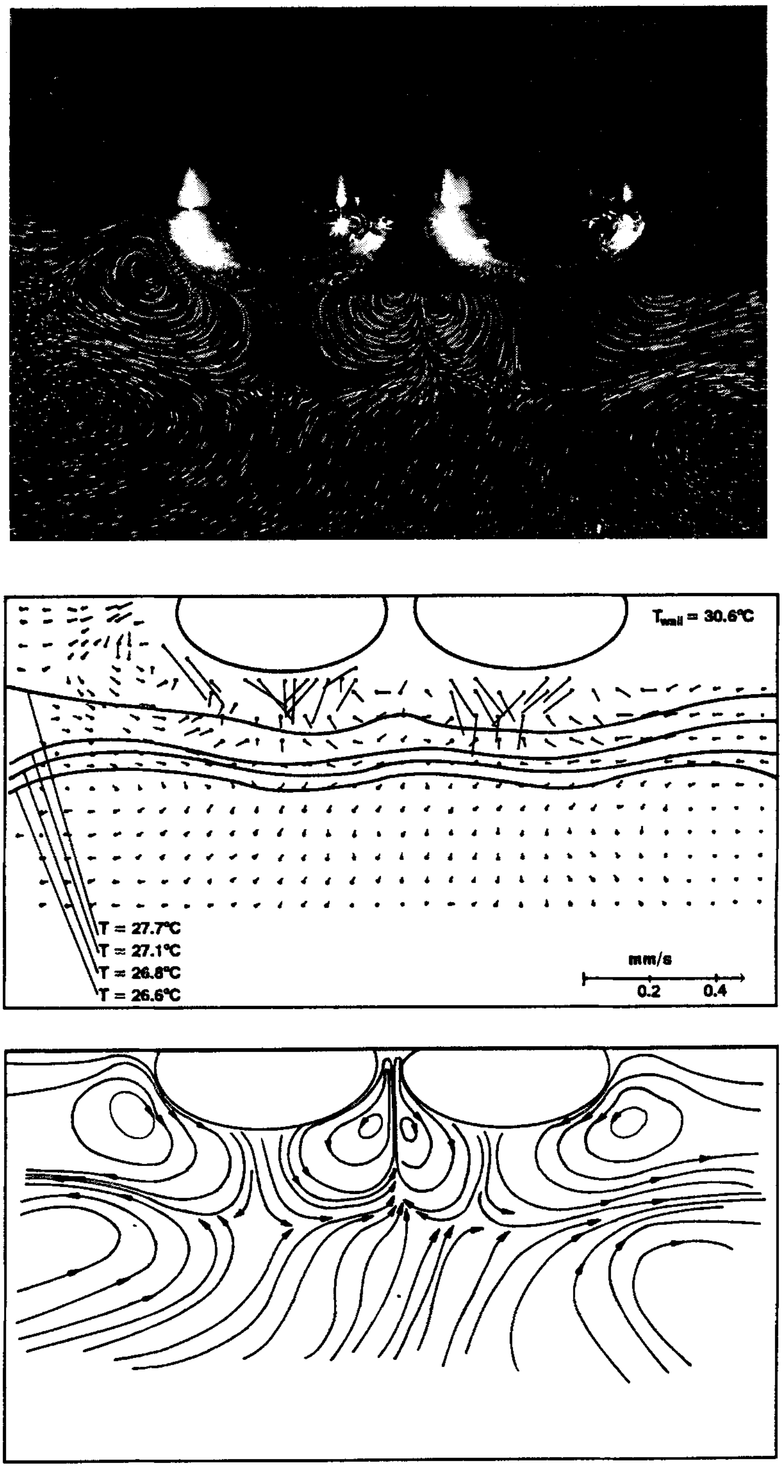

Figure 5. Results of the bubble experiment (ii).

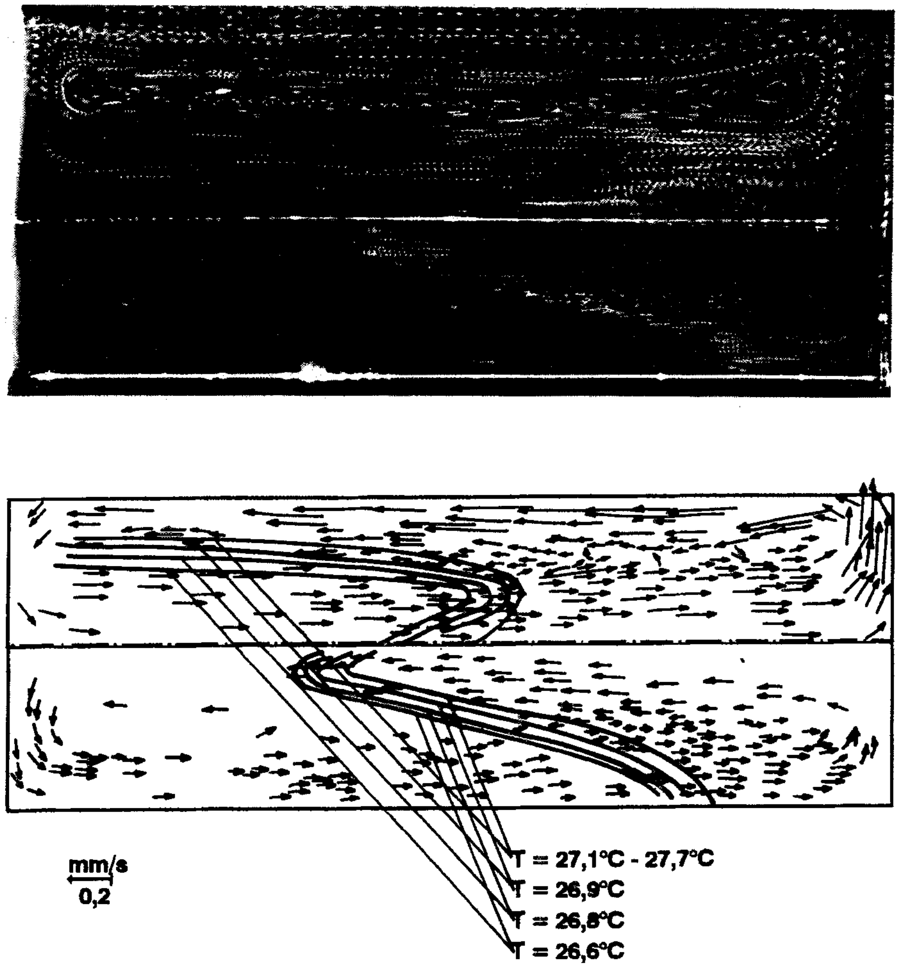

Figure 6. Results of the double layer fluid system experiment (iii).

exhibits two symmetrically arranged vortices within the illuminated plane which are driven by buoyancy and thermocapillarity, respectively. The relatively large particle displacements near the bubble contours distinctly demonstrate that the bubble surface is the principle driver of the flow. The shape of the flow is in qualitative agreement with results described in [2] and [9]. Isotherms, the velocity distribution and reconstructed streamlines are shown in Figure 5. The velocity information has been obtained by virtue of a particle tracking evaluation.

CONFIGURATION (III)

The multiexposed colour image of the double layer fluid system and its evaluation is shown in Figure 6. The height of the upper layer is 8 mm and the one of the lower layer 6 mm. Four isotherms are superposed on the velocity vector diagram. The horizontal temperature gradient ($\nabla T = 2.7$ K/cm) within the test cell causes a surface tension driven flow at the interfaces, which is superimposed by buoyancy effects. An encapsulation of the lower layer with silicone oil stabilizes the lower fluid layer so that only one anticlockwise vortex appears. As indicated in Figure 1, an extremely thin secondary vortex appeared at the bottom of layer 2, which could not be visualized by the use of tracers. It turned out that an encapsulation suppresses the strength of the flow significantly.

Concluding Remarks

A novel visualization technique has been applied, which allows to capture temperature and velocity field data of thermo-convective liquid flows simultaneously on a single chromatic image. Besides determining the quantitative velocity field we obtained four isotherms of the respective flow configuration. Due to the relatively simple and rapid experimental performance we may recommend this technique of flow visualization for buoyancy and thermocapillary liquid convection investigations. Due to the simple and compact experimental set up the described technique is predestined for space applications. Regarding the evaluation technique we intend to automate the tracer colour evaluation using computational methods. In summary, the simultaneous measurement of temperatures and velocities using thermo-sensitive liquid crystal tracers holds a high potential for the analysis of even complex thermo-convective flows

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