# INFRARED AND LIQUID CRYSTAL THERMOGRAPHY IN NATURAL CONVECTION

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**Keywords**: *infrared thermography, liquid crystals thermography, natural convection*

## Abstract

*The aim of the presented study is to test the simultaneous application of two acquisition methods, namely Particle Image Velocimetry & Thermometry combined with Infrared Thermography in an experimental investigation of natural convection. The first, based on liquid crystals tracers, allows full field temperature and flow analysis; the second is used to monitor Thermal Boundary Conditions at external non-isothermal walls bounding the flow domain.*

*Experimental and numerical studies have been made for transient and steady natural convection in a differentially heated cube filled with water. The analysis is carried out for pure convection of water in the vicinity of the freezing region (cold wall temperature $T_c = 0^oC$), and for convection of water accompanied by freezing ($T_c \leq -10^oC$). The opposite hot wall temperature is fixed at $+10^oC$.*

## 1. Introduction

Natural convection and phase change heat transfer such as melting and solidification are of interest in a wide range of technologies and practical applications, e.g. crystal growth from melts and solutions, heat transfer and fluid flow in nuclear reactors, purification of materials, latent heat energy storage for solar-heated housing and recently even in a solar dynamic power system for use in Earth-orbiting spacecraft.

In recent years, several experimental and numerical studies have been dedicated to natural convection in freezing water, indicating the complexity of the problem [1]. Its numerical modelling or experimental analysis is not an easy task. As a matter of fact, existing numerical codes appear to fail in modelling details of solidification. The numerical simulations performed by Banaszek et. al. [2], Kowalewski & Rebow [3], and most recently by Giangi et al. [4] show several differences in the front shape and front pattern. It seems that the numerical models need several improvements.

Among other model simplifications, a possible agent responsible for the discrepancies can be inaccuracy in modelling of the Thermal Boundary Conditions (TBC) at the "passive", non-isothermal side walls. Previous investigation, performed by the second author and co-workers [5,6], have shown that gentle natural convection can be extraordinarily sensitive to small changes in the TBC at the side walls. It appeared that only small variation of the TBCs change the direction and structure of the three-dimensional spiralling motion in the differentially heated cavity. The flow structure could be properly modelled only by applying to the numerical code the temperature fields measured at the side walls [7].

Complex flow structures, their sensitivity to small variation of the flow parameters, initial and boundary conditions require the application of appropriate experimental

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methods to validate the numerical results. It requires application of full field acquisition methods, which can give transient data for the velocity and temperature fields of the investigated flow.

Particle Image Velocimetry & Thermometry (PIVT), described in detail elsewhere [8], appears to be a valuable method for monitoring two-dimensional velocity and temperature fields within the flow. The method is based on the application of Thermochromic Liquid Crystals (TLC) suspended in a working fluid as seeding. Temperature and velocity maps so obtained can be compared directly with their numerical counterparts.

The aforementioned discrepancies between numerical and observed results force us to verify Thermal Boundary Conditions imposed on the “passive”, non-isothermal side walls of the cavity. To control heat flux through these walls, measurement of both internal and external temperature fields at these walls becomes necessary. Such a possibility is offered by combined application of Infrared and TLCs based Thermography. Temperature fields obtained by IRT at external walls, and internal temperature maps from PIVT measurements enrich our description of the physical experiment allowing better verification of numerical models.

To avoid geometrical complications and uncertainty of the thermophysical properties, a simple model of water freezing in a differentially heated cavity is considered. Our main goal is to test the applicability of both thermographic techniques in verifying the TBCs for the investigated flow. The experimental results obtained are compared with numerical simulation performed using the modified 3-D finite difference code FREEZE3D [9].

## 2. Formulation of the Problem

An experimental study has been made of transient and steady convection in a differentially heated cube-shaped enclosure with inner dimension equal to 38 mm (Fig. 1). Distilled water is used as a working fluid. Two opposite vertical walls are assumed isothermal. One of them is held at a temperature $T_c = 0^oC$, that is the freezing point of the liquid $T_r$, in the case of natural convection without phase change or below the freezing point = $10^oC$. The other four walls, made of 6 mm low thermal conductivity material (Plexiglas) allow the entry of heat from the external air. $T_c = -10^oC$ when ice growth is also analysed. The opposite vertical wall is held at a temperature $T_h$.

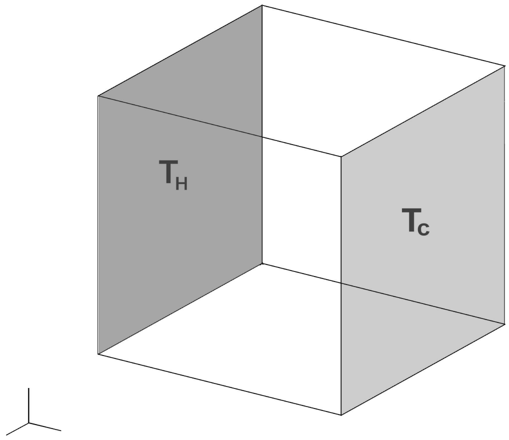



**Fig. 1. The cubical box with differentially heated walls.**

To make the heat transfer through the side walls well defined, a constant flux of air generated by a low speed fan was directed at the cavity. The temperature of the air stream is $T_{ext} = 23.8°C$.

Heat transfer from the gas environment through the Plexiglas walls is relatively low and its effect on the internal flow can be considered to be small. However, in the experiment the air temperature is well above the internal fluid temperature, and at least in the near wall regions this may apparently modify the flow.

The initial fluid temperature is equal to $T_o = T_h = +10°C$. A zero initial velocity flow field is assumed. The convection starts when at time t=0 the cold wall temperature is suddenly decreased to $0^oC$ in the convection or $-10^oC$ in the freezing experiments.

Three basic dimensionless parameters defining the freezing problem driven by both conduction and free convection are the Rayleigh number (Ra), the Prandtl number (Pr) and the Stefan number (Ste), given as

$$Ra = \frac{g\,b\,\Delta T H^3}{a\,n}\ , \quad Pr = \frac{n}{a} \quad \text{and} \quad Ste = \frac{c_p\,\Delta T}{L_f}\ ,$$

where $DT = T_h - T_r$ is the difference between the temperatures of the hot wall $T_h$ and the phase interface $T_r$. In the above definitions $g$, $H$, $\alpha$, $\beta$, $\nu$, $c_p$, $L_f$, denote, respectively, the gravitational acceleration, the cavity height, the thermal diffusivity, the coefficient of thermal expansion, the kinematic viscosity, the specific heat and the latent heat of fusion.

Due to the temperature dependent fluid properties, especially the strongly non-linear variation of water density, the non-dimensional description of the problem becomes only formal. For such a description, the physical properties of the fluid are taken for the arbitrary selected reference temperature $T_r=0^oC$. The corresponding non-dimensional values calculated for temperature difference $DT=10^oC$ and *38 mm* cavity are: $Ra=1.503 \cdot 10^6$, $Pr=13.3$, $Ste=0.125$.

## 3. Test apparatus and experimental procedure

The experimental set-up is sketched in Fig. 2. The cubic convection box has two isothermal walls made of a black anodised metal. Their constant temperature is maintained by anti-freeze coolant flowing through the attached antechamber. The temperature of the cooling and heating liquids are controlled by two thermostats. Seeding with thermochromic liquid crystals is used, allowing instantaneous measurement of the velocity and temperature to be made.

For the flow visualization the cavity is illuminated with a 2 mm thick sheet of white light from a specially constructed halogen lamp. The colour images of TLCs flow seeding are observed in the perpendicular direction by a 3CCD *RGB* camera (Sony XC-003). The 24-bit images of 768x564 pixels resolution are acquired using a 32-bit frame grabber (ITI).

The infrared images of the front side wall are acquired with a low wavelength infrared scanner Agema 900, and used to evaluate the temperature field at the external surface of the wall. The IR Images of the cavity were taken from 110 mm distance. Due to the space constraints, in the present configuration it is impossible to obtain images from the RGB and the IR camera simultaneously. Hence, a computer controlled system of three stepping motors is used to move the cavity and the *RGB* camera. It allows the acquisition of flow images of two different vertical cross-sections (near the front wall and at the centre of the cavity), and two infrared images of the front wall. The images are taken fully automatically within 10 seconds. The relatively long relaxation time of the flow allows us to assume that all images are taken at the same instance.

### 3.1 Particle Image Velocimetry & Thermometry

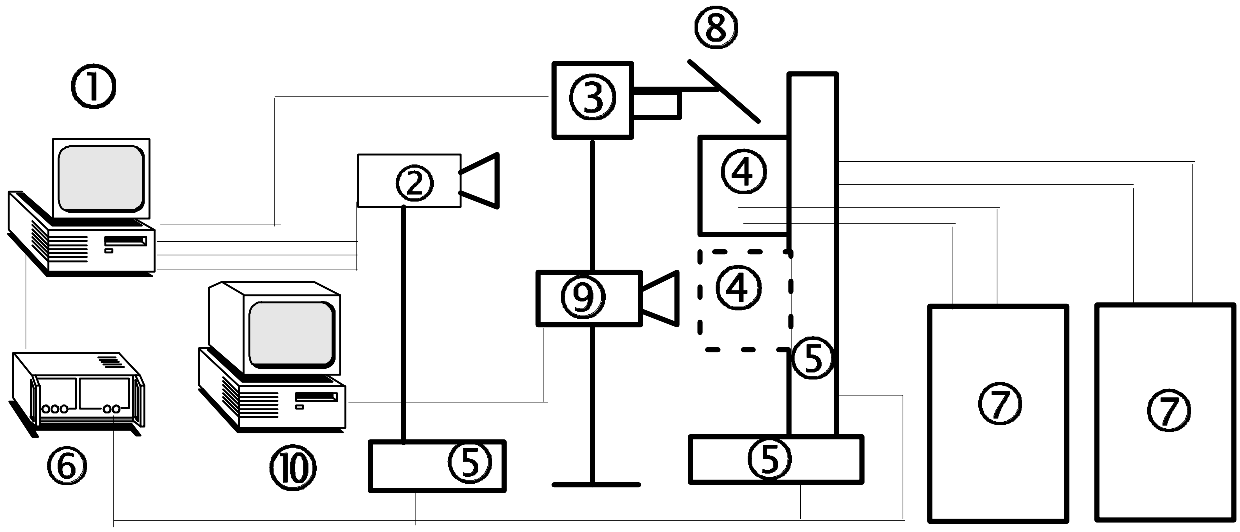



**Fig. 2. A schematic view of the experimental set-up. PC (1) with the acquisition card controlling camera (2), halogen lamp (3) and three stepping motors (5) using driver (6). Temperature in the cavity (4) controlled by two thermostates (7). Mirror (8) used to direct light sheet. IR camera (9) and IR controller (10)**

As mentioned previously Thermochromic Liquid Crystal tracers dispersed in water have been applied to measure both temperature and velocity flow fields. The mean diameter of unencapsulated TLC droplets sphere is about 50um. Their density being close to that of water and relative intense light scattering predispose the TLCs suspension as useful tracers for the flow visualization.

Digital Particle Image Velocimetry is used to obtain the velocity vector field from the flow images. For this purpose, the colour images of TLC tracers are transformed to B&W intensity images. After applying special filtering techniques [10] bright images of the tracers, well suited to DPIV, are obtained.

For simultaneous measurement of the two-dimensional temperature field, the Digital Particle Image Thermometry (DPIT) is used. It is based on computer-aided evaluation of the digital *RGB* flow images. To evaluate temperature the generally applied [6,11] *HSI* (Hue, Saturation, Intensity) conversion of *RGB* images is used. Temperature is determined by relating the hue to a previously obtained temperature calibration curve [12].

The colour play interval of TLC used was selected to cover a temperature range from about 2$^{o}$C to 5$^{o}$C. Due to the strong non-linearity of the hue-temperature relation, the accuracy of the measured temperature depends on the hue value, and varies from about 3% to 10% of the full colour play range.

TLCs are widely used for surface thermography [13,14], however their application for measuring temperature of external walls of the cavity appeared non-practicable. Covering the side walls with a TLC layer or a special TLC sheet would strongly reduce the optical access, and diminish or totally eliminate the possibility of resolving internal temperature and velocity fields. Hence, the Infrared Thermography appears to be the only usable full field measuring technique at the moment.

## 3.2 Infrared Thermography

Infrared thermography is a well established measurement technique for two-dimensional thermal maps. It has been successfully employed to measure convective heat fluxes in both steady and transient techniques [15].

The system used in our experimental studies consists of a low wavelength Agema Thermovision 900 LW infrared scanner. It uses a Mercury Cadmium Telluride (MCD) detector with liquid nitrogen cooling. The spectral band covered is from 8 to 12 μm, with some residual response outside this range. This spectral response results in low noise level measurements at room temperature. Nominal sensitivity of the scanner is equal to 0.08°C at 30°C. Our careful correction procedure, using thermocouples and precise surface temperature measurements allowed us to reach accuracy equal to 0.3°C.

The scanner image resolution is 200 elements by 136 lines. Each image is digitised in a frame of 272 x 136 pixels at 12 bit. Application software (Erika) allows selection of useful dynamic range of images and converts them to 8-bit TIFF images. The software allows adjustment of temperature range, choice of colour palette and preliminary image analysis.

The scanner used with a 20° x 10° lens and a close-up lens has a resolution of 0.23 mrad. To improve the spatial resolution of images, the analysed field is acquired in two steps. The first IR image covers the lower half of the investigated side wall, the second image the upper half. The computer controlled system of stepping motors moving the cavity, allows us to minimize the interval between both images to about 2s. Specially developed post-processing software is used to merge both half images to one full image of the wall with a resulting resolution of 272 x 272 pixels.

Due to continuity of the observed thermal field, IR images of the cavity show a relatively smooth transition of grey levels. This creates potential difficulty or inaccuracy in recognizing the geometry of the analysed object. To simplify post-processing of images (and their merging), small metal markers (visible in reproduced figures below) are attached at four sides of the wall. The markers are insulated from the wall, hence well visible due to their different temperature. Comparing the IR and RGB images of the front wall, the exact geometry of the cavity could be well identified.

## 4. Numerical Model

The obtained empirical results are further used to verify the performance and accuracy of the Finite Difference model developed to simulate natural convection with solidification. A modified version of the three-dimensional numerical code FREEZE3D (Yeoh 1993) has been used. The governing equations of a Newtonian fluid are those from the physical conservation laws of mass, momentum and energy. The main fluid properties, viscosity, thermal conductivity, specific heat and density are given functions of temperature. However, the density variation is applied in the buoyancy term only. The thermal properties of ice were assumed constant. The thermal conductivity, heat capacity and density of the Plexiglas used for the side walls were measured [7].

For the fluid domain the vorticity-vector potential formulation is used in the code. The independent variables are vorticity and the vector potential, whereas the pressure is eliminated and the continuity equation is automatically satisfied.

The governing equations are solved separately for the fluid and solid domain using a curvilinear co-ordinate system filling the physical domain. As the physical domain changes shape, the interface boundary grid is generated at each time step. The boundary fitted grid is smoothed using the elliptic grid generation method. In solving the time dependent partial differential equations, an Alternating Direction Implicit (ADI) method which marches in time is employed. The vector-potential equation is solved using a successive over-relaxation (SOR) method at each time step. A second order central difference approximation for spatial derivatives and a forward difference approximation in time are used.

When simulating experimental conditions, the main problem which arises is the proper definition of the thermal boundary conditions. Two opposite walls are isothermal. Four other walls are made of 6mm Plexiglas. To approach as close as possible physical conditions, the code was modified by implementing the side walls into the computational domain. A separate energy equation is solved for the heat transfer from the external air through the four side walls.

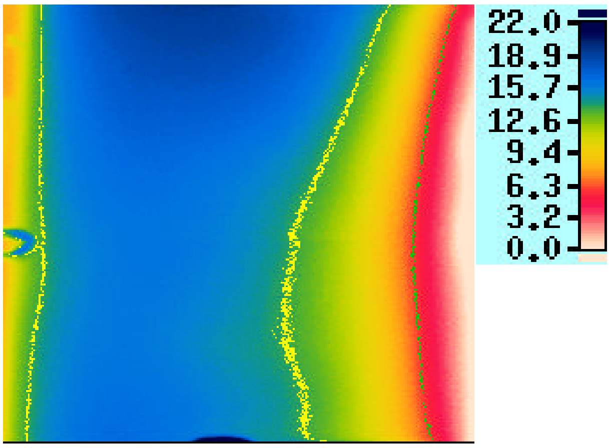
Solutions are obtained using 31x31x41 mesh points. $21^3$ mesh points are used for the fluid domain, 5 additional mesh points at each side for the Plexiglas walls, and 21*x*21*x*10 mesh points for the ice domain. To test the mesh dependence selected cases were calculated increasing the number of grid points to $31^3$ for the fluid domain. To start the freezing calculations the initial grid for the solid phase must exist. Hence, it was assumed that at the first instant the cold wall is already covered with an ice layer of non-dimensional height 0.02.

## 5. Results

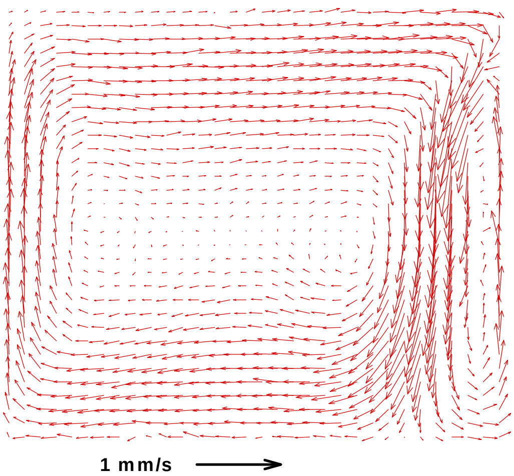
### 5.1 Natural Convection

At the beginning, our interest was directed to understanding the transient behaviour of natural convection of water in the vicinity of the freezing point. The experiments start by abruptly dropping the cold wall temperature to $0^{o}$C. The effects of density inversion and of the thermal boundary conditions at non-isothermal walls on the flow structures are studied to compare and eventually improve the numerical code.

A typical flow structure exhibits two circulation regions, where the water density decreases with temperature (upper) and an abnormal density variation (lower). It was found that the calculated flow pattern depends strongly on the modelling of the thermal boundary conditions at the side walls. Neither isothermal nor constant heat flux models are sufficiently accurate to obtain the observed flow structures. The IR measured distribution of temperature at the external surface of the side wall (Fig. 3) indicates non-uniformity of the heat flux, which may be the possible reason for observed discrepancies. By resolving temperature differences recorded across the wall, additional hints about the thermophysical properties of the Plexiglas walls as well as about assumed air/wall heat transfer coefficient will be obtained.




a

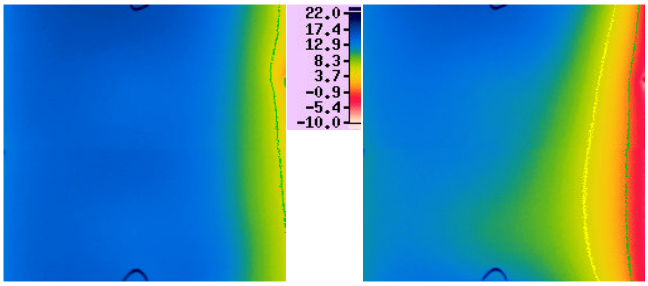



b

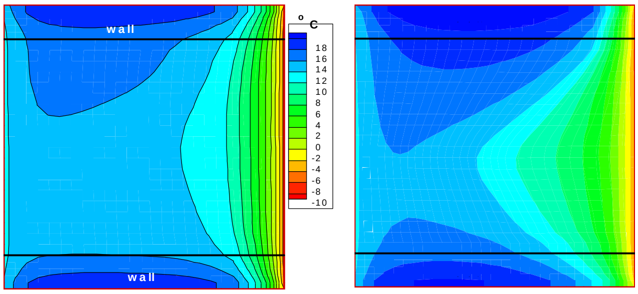
**Fig. 3. IR thermographic image with two isothermal lines green 6 °C and yellow 14°C (a) of external surface of the side wall and velocity field (b) at the vertical centre plane z=0.5 for free convection of water at 2400 s after start of cooling; Tc=0 °C, Th=10°C, Text=23.8°C.**

## Freezing of Water

The pure water freezing experiments show, as already mentioned, two main flow circulation regions. In the first, driven by „normal convection" and located in the upper part of the cavity, there is a clockwise circulation. It transports the hot liquid up to the top wall and back along the isotherm of the density extreme. Interaction of the hot liquid with the freezing front causes its melting and depletion of the freezing plane. The second flow circulation region, due to „abnormal convection", is located in the lower part of the cavity. There, a counter-clockwise circulation transports the cold liquid up along the adjacent ice surface and back to the bottom along the isotherm of the density extreme. This cold water circulation only moderately modifies the heat balance at the interface. The convective heat transfer between both upper and lower regions seems to be limited mainly to the upper right corner of the cavity. There, along the colliding cold and warm fluid layers, the heat is transferred from the hot wall to the lower parts of the cavity. The shape of the freezing front reproduces this interaction, almost doubling the ice growth rate at the bottom (comp. Fig. 5).




a b




c d

**Fig. 4. Freezing of water. IR thermographic images with two isothermal lines green 0 °C and yellow 6°C (a) and (b) and numerical solution of temperature distribution on the vertical side wall (c) and (d) at 500s (a) and (c) and 3600 s (b) and (d) after start of cooling; Tc=-10°C, Th=10 °C, Text=23.8°C.**

The temperature distribution at the side walls is shown in Fig. 4. Comparing calculated and IR measured fields we may recognise the main features, the characteristic "belly" of the isotherms close to the cold wall. The heat flux through the top and bottom walls increases the temperature in adjacent fluid layers. This in turn modifies the overall circulation pattern, shifting the position of the ice front back to the cold wall (Fig. 5). However, the numerical simulation seems to overestimate this effect. Observed and calculated ice fronts are different. Hence, also the temperature and velocity fields are only qualitatively similar.

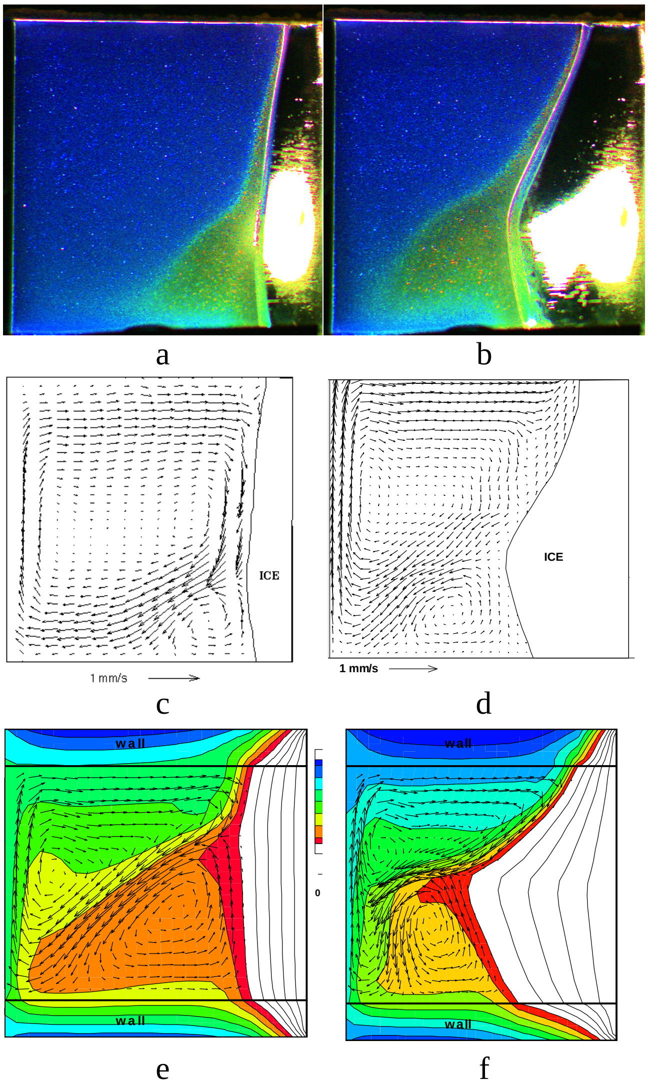



**Fig. 5. Freezing of water. TLC tracers (a) and (b), velocity filed (c) and (d) and numerical solution (e) and (f) at the vertical centre plane z=0.5 at 500s (a), (c) and (e) and at 3600 s (b), (d) and (f) after start of cooling.**

Direct implementation of the IR measured thermal maps of the external surfaces to the code may clear out doubts about proper modelling of the TBC. However, there are other possible agents, responsible for the difficulties encountered in modelling freezing of water. Further studies are necessary to verify the assumptions made and to consider in the modelling the following effects:

- Fluid supercooling, these effect is observed experimentally and may be of primary importance. Hence, numerical modelling of the nucleation delay time seems necessary.
- Thermal boundary layer at the interface.
- The colliding boundary layer, appearing due to the density anomaly of water at the cavity diagonal boundary layer between hot (clockwise) circulation and cold (anti-clockwise) circulation.
- Imperfections in the solidus structure, non-homogeneity and layering.
- Non-ideal thermal contact between the solidus and the box cooled surfaces.
- Verification of the available thermophysical data. Effect of their inaccuracy on the numerical result.

## 6. Final remarks

The infrared technique allowed the measurement of temperature with an accuracy better then 0.3$^{o}$C. The accuracy of temperature measurements obtained with the help of liquid crystal tracers varies from 0.2 $^{o}$C to 0.6 $^{o}$C, depending on the colour play range. It was found that the temperature fields measured at external surfaces of the side walls as well as those of the top/bottom walls are far from being uniform. The observed temperature pattern reflects that visualised inside the cavity with help of liquid crystal tracers. The heat transfer through the walls estimated from both measurements is compared with the assumptions made in the numerical simulations. The detailed comparative analysis of numerical results and experimental findings appears to be a unique alternative allowing the understanding of the limitations of the numerical model and giving indications concerning its improvement.

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## Movies:

1. Freezing of water. Temperature distribution on the vertical side wall measured using IRT during 7000 s period. ***Tc=-10°C, Th=10°C, Text=23.8°C. (comp. Fig. 4)***

2. Freezing of water. Numerical solution at the vertical centre plane z=0.5 during 3600 s. **Tc = -10°C, Th=10°C, Text=23.8°C (comp. Fig. 5)**