- **The aim $\Longrightarrow$ to explore both experimentally and numerically natural convective flow in a cubical cavity with a free surface. It seems useful to understand the main features of the free-surface flow under on Earth conditions.**

- **Experiment $\Longrightarrow$ box 50mm, two opposite vertical isothermal (metal) walls, the other four walls made of 8mm plexiglas. 90% of the cavity height is filled with water-glycerin solutions leaving small gap of air between its top wall and the fluid surface.**

- **Computation $\Longrightarrow$ a finite difference model of the Navier-Stokes and energy equations.**

**For comparison the parallel investigations were performed with the upper part of the cavity closed by an additional plexiglas plate.**

**Range of the basic dimensionless parameters,**

**the Rayleigh number (Ra) and the Prandtl number (Pr):**

$$Ra = \frac{g\beta(T_h - T_c)L^3}{\kappa\nu}, \qquad Pr = \frac{\nu}{\kappa} \tag{1}$$

**Ra = 22000 - 395000**

**Pr = 752 - 8900**

**The effects of surface tension $\sigma$ at the free surface are neglected.**

**The Marangoni number (Ma) and the Bond number (Bo):**

$$Ma = |\frac{\partial\sigma}{\partial T}|\frac{(T_h - T_c)L}{\kappa\nu\varrho}, \qquad Bo = \frac{g\varrho L^2}{\sigma}. \tag{2}$$

**are**

**Ma=99 - 2060, Bo =492.**

**In the above definitions $g$, $L$, $\kappa$, $\beta$, $\nu$, $\varrho$ denote respectively the gravitational acceleration, the cavity length, the thermal diffusivity, the coefficient of thermal expansion, the kinematic viscosity and the density.**

## EXPERIMENTAL METHODS

**1. Simultaneous Quantitative Measurement of**

**Entire 2D Velocity and Temperature Fields:**

**Digital Particle Image Velocimetry (PIV) & Particle Image Thermometry (PIT)**

**2. Visualization of particle tracks:**

**adding saved images and real time "on board"; accumulation of differential images.**

| | |
|---|---|
| **Flow medium:** | **glycerin and 87% aqueous solution of glycerin** |
| **Temperature range:** | $T_c$=25 – $T_h$=30$^oC$ and 26 – 29$^oC$ |
| **Flow seeding:** | **Thermochromic Liquid Crystals (TLC):** |
| **size:** | **ca. 50** $\mu m$ |
| **response time:** | $<$ **0.05s** |
| **density:** | **ca. 1g/cm$^3$** |

**ACQUIRING SYSTEM:**

- **1kW halogen line lamp: 100 mm $\times$ 2mm light sheet, illumination time: 40ms**
- **Light sheet observed at 90$^o$ with 50 mm lens by 3 $\times$ CCD RGB camera (JVC KYF55)**
- **VFG100 3 $\times$ input (RGB) Imag. Tech. Inc. frame grabber.**

**Resolution:**

**3 $\times$ 768$\times$ 512 $\times$ 8 bit for single image.**

**METHODS USED:**

- **Stationary or slowly varying flow:**

  **multiple imaging, i.e. a sequence of 4-8 images is taken at constant or varying time intervals.**

- **Fast transient:**

  **double imaging, i.e. two images taken at interval $\Delta t \geq$ 1ms**

**EVALUATION TECHNIQUES:**

- **PIT - measured hue values at mesh points are smoothed by averaging, filtering, erosion-dilation of "black-holes", smoothing.**

  **Contouring according to the given calibration curve.**

  **PIT calibration constrains:**

  **- the same illumination**

  **- the same acquiring optics**

  **- the same LC properties**

  **Relative temperature error: 5% -15% of the full temperature range.**

- **PIV - background subtraction, preprocessing of R,G,B images using "local binarization", interpolated intensity image from three components, oversampling by image doubling.**

  **Cross-correlation of image pairs using FFT, $64 \times 64$ interrogation sections with 16 or 32 pixels step.**

  **Reconstruction of velocity fields for multi-image pairs of a long sequence.**

  **Velocity vectors validation:**

  **- mean deviation**

  **- "quality factor"**

  **- continuity equation (test)**

  **Relative velocity error $\approx$5% .**

## NUMERICAL PROCEDURE

**Vorticity-vector potential ($\vec{u} = \vec{\nabla} \times \vec{\Psi}$) formulation of the 3-D Navier-Stokes and energy equations:**

$$\frac{1}{Pr}\{\vec{\nabla} \times [\,\vec{\omega} \times (\vec{\nabla} \times \vec{\Psi})]\} \;=\; -Ra\,[\vec{\nabla} \times (\Theta\vec{e}_y)] + \Delta\vec{\omega} \quad , \tag{3}$$

$$((\vec{\nabla} \times \vec{\Psi}) \cdot \vec{\nabla})\Theta \;=\; \kappa\,\Delta\Theta \quad , \tag{4}$$

$$\Delta\vec{\Psi} \;=\; -\vec{\omega} \quad . \tag{5}$$

**Wall–Fluid Thermal Boundary Conditions in the general form**

$$a\Theta + b\frac{\partial\Theta}{\partial n} = c$$

$a$, $b$ **and** $c$ **varied to specify the boundary condition existing in the experiment.**

**CONCLUSIONS:**

- **The method of simultaneous PIV & PIT allows whole field verification of experimental and numerical results.**
- **The overall agreement between calculated and measured flow characteristics is satisfactory for the center plane.**
- **The free surface increases flow velocity at the top hot-corner. The temperature gradients at the surface are shifted into the cold wall. Flow below, in the centre and lower parts of the cavity, remains almost unaffected.**
- **The observed recirculating flow at the surface is not found in the numerical simulation. Neither relatively strong effects of the variable fluid viscosity, nor non-adiabatic thermal boundary conditions produce observed recirculating flow at the surface.**
- **Surface flow stratification is observed for wide range of parameters. Excluding thermocapillary flow, the possible hypothesis is so called surface viscosity combined with yield stress necessary to remove molecules from the surface to the bulk flow.**