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Measurement of Simulated Convective Temperature Distribution Near Ancient Wall Paintings

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***Abstract*:** This study presents a method for measuring the temperature distribution in a confined volume of water used to simulate heat convection in the air. The water was seeded with thermo sensitive crystals as an indicator for the temperature. A 1:10 scale model of a room cross section was used in the study. The model was fitted with the heating elements to produce a heat flux similar to that produced by heating radiators at full scale.

Thermo-sensitive Liquid Crystals (TLC) were "in-situ" calibrated using a standard temperature gauge. The obtained response function was used to relate the colour of the TLC with the ambient temperature.

The resulting temperature distribution was recorded at several instants during the heating process. Using this approach the evolution of the temperature distribution was visualized.

***Keywords*:** thermo-sensitive liquid crystals, natural convection, air modeling in water.

Nomenclature:
$g = 9.81\ ms^2$ - gravitational constant
l - characteristic dimension
r - Density
b - Expansion ratio
n - Kinetic Viscosity
T - Temperature
a - Thermal Diffusivity

1. Introduction

This investigation deals with temperature distribution measurements in the closed rooms which are warmed by local heaters. The goal of this investigation was to establish a method for temperature field mapping inside such a room volume using TLC Image Thermometry.

In the present case, the main reason for undertaking the study was to determine the influence of the heating systems in the preservation of wall paintings in the Hardham Church St. Botolph's, England. This church was constructed around 1100 AD and is located south of Pulborogh. The church is used four times per month and heated up for that reason. With the current heating system in the church, the wall paintings are being damaged slowly by the heating and cooling cycle as air circulates past them.

Similar experimental work of airflow visualization, using steam for visualization is described in Wisniewski et al. (1998). 3D Particle Streak Velocimetry has also been applied by Scholzen and Zuerich (1997) to collect information about airflow with the goal of optimizing the heating system while minimizing environmental pollution.

A combination of theoretical and experimental studies of movement of air indoors is described in Scholzen and Zuerich (1997) where boundary conditions and convection above a heat source are also described.

In the present work a 1:10 model of a room was used with air replaced by water and seeded with TLC (Thermo-sensitive Liquid Crystals). Comparison of physical properties of both mediums was made and scaling parameters for different conditions were calculated. The model used had two internal heaters and submerged into a larger tank to aid simulation of ambient conditions.

2. Comparison of the Physical Properties of Water and Air

2.1 Natural Convection

The configuration of the temperature field in a moving medium depends essentially on the configuration of the velocity field. In this connection, a distinction is made between forced convection — when the motion of the medium is governed by some external force, and free convection — when the motion of the medium is governed purely by the processes of heat transfer and buoyancy forces.

The presence of a temperature field also causes a variation in the viscosity of the fluid, which is also related to the configuration of the velocity field.

Thus, the temperature and velocity fields in a moving fluid are a consequence of thermal and mechanical interaction. The temperature field will always depend on the velocity field; there is no converse dependence in a number of cases of forced flow of the medium. The influence of the temperature field on the velocity field is therefore often neglected under conditions of forced convection and only the converse effect is taken into account.

All true liquids can be considered incompressible, as well as gases, if the flow velocity of the latter is much less than the velocity of sound. Heat transfer in these conditions may be described by the following parameters of similarity (Kutateladze and Borishanskii, 1966).

$$Nu = f(Pr, Gr, \text{shape of body}) \tag{1}$$

$$Gr = \frac{g \cdot l^3}{n^2} \cdot b \cdot DT \tag{2}$$

$$Pr = \frac{n}{a} \tag{3}$$

The Nusselt number (Nu) is the dimensionless heat transfer coefficient. The Grashof number (Gr) characterizes the interaction of molecular friction and the buoyancy force imposed by the difference in densities at different points in a non-isothermal stream. The Prandtl number (Pr) is a parameter for the similarity of a temperature and velocity field.

In gases and non-metallic liquids ($Pr \approx 1$), the thermal resistance is concentrated in a thin boundary layer on the surface in which molecular friction predominates (Kutateladze and Borishanskii,1966). Thus, the set of equations for thermal conductivity and motion may be simplified giving only one defining parameter

$$Pr \cdot Gr = \frac{g \cdot l^3}{n \cdot a} b \cdot Dt. \tag{4}$$

2.2 Scaling Parameters

Having these equations, and provided that properties of air are taken at average temperature of 20 ;, it is possible to calculate a temperature scale for given geometrical scale (G_{scale}) - (Eq. 5). Consequently, the corresponding temperature difference in the air may be calculated (Eq. 6).

$$T_{\text{scale}} = \frac{\dfrac{g \cdot b_W(T)}{n_W(T)^2} \cdot Pr_W(T)}{\dfrac{g \cdot b_A(20°)}{n_A(20°)^2} \cdot Pr_A(20°)} \cdot G_{\text{scale}}^{-3} \tag{5}$$

$$DT_{\text{air}} = T_{\text{scale}} \cdot DT_{\text{water}} \tag{6}$$

Figure 1 shows temperature scale calculation, based on the physical properties of water and air taken from Raznjevic (1976). T_{scale} is about 3.84 for water temperature near 30;, meaning that the temperature change in air is approximately 3.84 times smaller than in water.

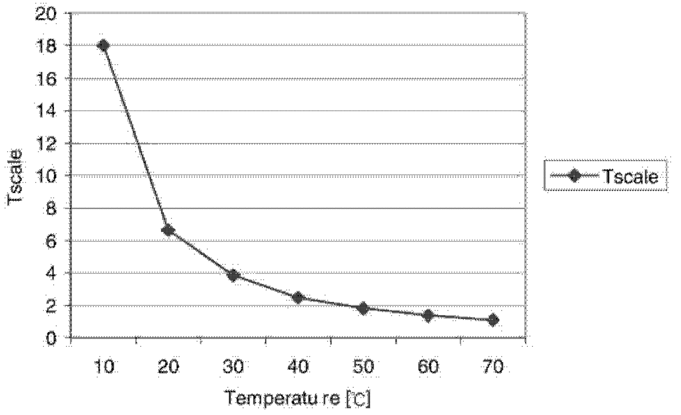

Fig. 1. T_{scale} dependence to the temperature for geometrical scale 1:10.

By using a lower working temperature during the experimental work, the temperature multiplication factor will be higher. This is related to a smaller measurable temperature difference in air, a consequence of the fixed working range in water that is fixed by the bandwidth of the TLC.

3. Experimental Setup

3.1 Experimental Setup

The experiment was simplified initially using the assumption that 3D geometry of the room was reduced to a 2D problem by model design making assumptions of effectively infinite length of the room in the direction of the longer side. The heating rate was not calculated exactly to equal to the existing heating system in the room, but simply based on available heating systems meaning that the rate of developing temperature distribution in the model did not exactly scale to full scale. This limitation may be removed by an exact modeling of the heating power and applying a time scale according to the geometrical scale.

The model consisted of two boxes made of 'Plexiglas,' each filled with water and both equipped with an independent heating system. The outer box represented the ambient environment outside the church. The inner box, the convection box, represented the room and was seeded with TLC. The thickness of the side-walls was calculated in order to model the heat transfer through the walls of the room. The front and the back walls of convection box were made 20 times thicker than the side walls to exclude heat exchange in these directions consistent with the 2D modelling approach. Both boxes were fitted with heating elements to simulate the room heating system, and external conditions. For the future investigations a cooling system for outer box may be used to keep the temperature of the outside box stable, providing constant heat flux through side-walls. By using both heating systems, different temperature conditions may be modelled. The model schematics are shown in Fig. 2.

For the calibration and experimental work of this investigation, the microencapsulated chiral nematic slurry R29C4W from Hallcrest (1820) was used. The working range of this TLC starts at 29; and has a bandwidth of 4;. This product contains 40% solid slurry in water with microencapsulated TLC of a diameter 100 mm. The liquid crystals are added to a refined water to a volume concentration of 0.01%.

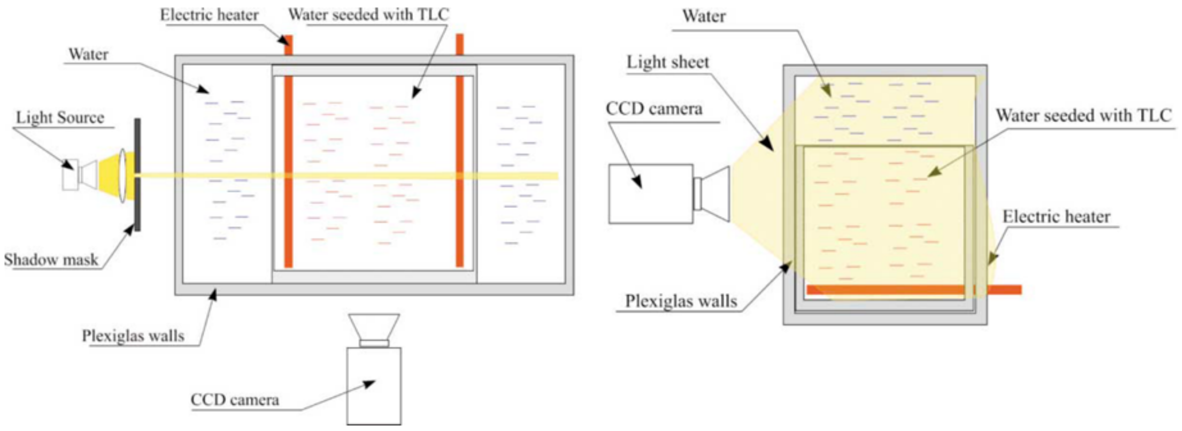

Fig. 2. Experimental setup, top view and side view.

The illumination was provided by a halogen lamp to produce a vertical light sheet having 10 mm thickness, formed by a lens and a shadow mask. The angle between the optical axis of the CCD camera and the light sheet was set to 90¡. The images were taken by a CCD camera, which was placed in front of the boxes and fitted with long focal length lens to minimize the colour change with the angle of view. This later point is of great importance in the application of the TLC method (Fujisawa et al., 1998; Ohue et al., 1998; Kowalewski, 1998; Wilcox et al., 1985). The distance between camera and experimental setup was set to 4 meters, giving angle of view of 5 degrees. The spatial resolution of the CCD camera was 768 × 568 for each component R, G, B of colour. The captured colour images were digitized by a frame grabber installed in a PC and stored for further image analysis. A series of the images were averaged to reduce the noise of ADC process in the frame grabber. The colour images captured in RGB space were converted into a HSI colour space by the algorithm described in Vishnevski.

3.2 Calibration Setup

The calibration of TLC was performed under the same conditions as in the experiment. This was necessary because of high sensitivity of TLC to the relative position of light source and position of the camera (Fujisawa et al., 1998). The inner box was fitted with thermocouples and control images were taken as well as independent measurements of temperature — see Fig. 3.

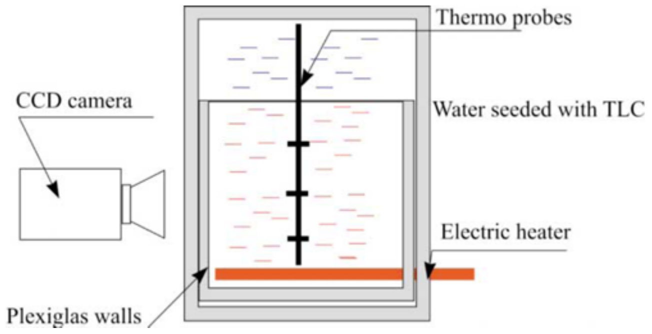

Fig. 3. Calibration setup.

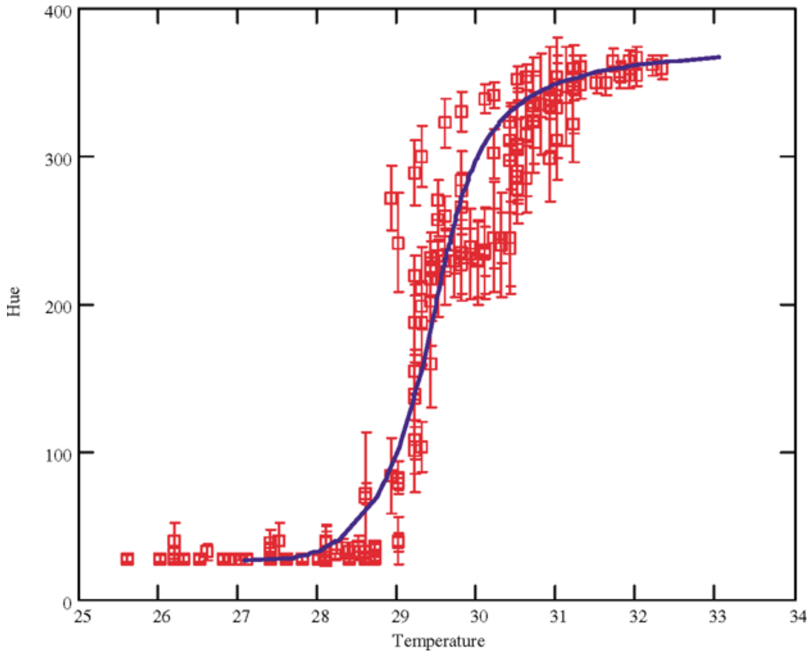

Fig. 4. Response of TLC.

Figure 4 shows the optical characteristics of the liquid crystals used in the experiment, which indicates the variation of hue with the measured temperature. The Hue was chosen to be the calibration parameter because saturation and intensity of the TLC are heavily affected by non-uniformity of illuminating light and noises in the ADC unit of the frame grabber. To build the calibration curve (Fig. 4) a least-square approximation (Press et al., 1992) was used with the basis functions {1, tan(t), ln(t)} making the approximation function shown in Eq. (7). The basis chosen shows smaller mean error than a polynomial data fitting. The figure also shows mean deviation of Hue at each measured temperature.

$$f(x) = a_0 + a_1 \cdot \tan\left(\frac{x-180}{400} \cdot p\right) + a_2 \cdot \ln\left(\frac{x-26}{10}\right) \tag{7}$$

4. Results

Figures 5—8 show the original pictures from the frame grabber, averaged among 4 sequential frames to reduce noise. Saturation of the pictures was enhanced for demonstration purposes. Figures 9-12 show calculated temperature distributions. Figures in (a) series show an experimental setup with a flat roof; series (b) were taken with a peaked roof. The sequence of pictures shows heating up process in each case, so Figure 9 corresponds to the lowest mean temperature and Figure 12 to the highest. Roof shape creates significant difference in the temperature field distributions on the initial phase of heating process what is quite feasible and proves efficiency of the measurement approach. Transition from Hue Field Presentation to the Temperature Field Presentation enhances visualization and provides results for future heat transfer estimations.

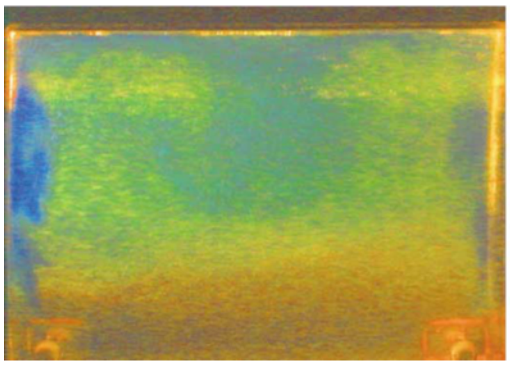

Fig. 5(a)

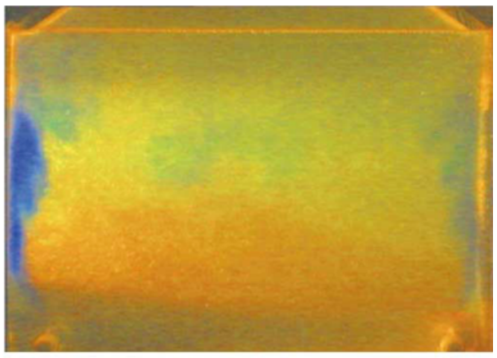

Fig. 5(b)

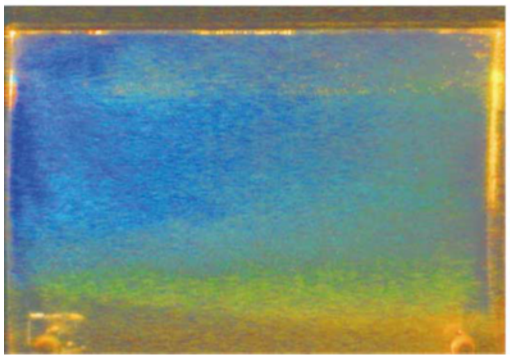

Fig. 6(a)

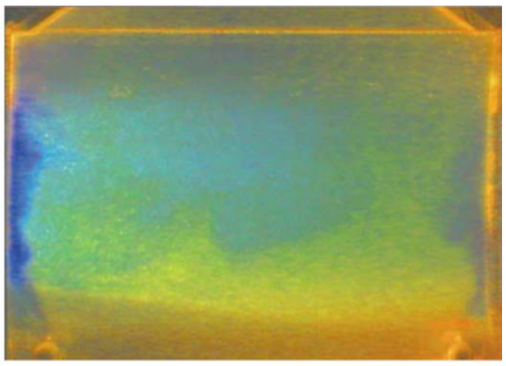

Fig. 6(b)

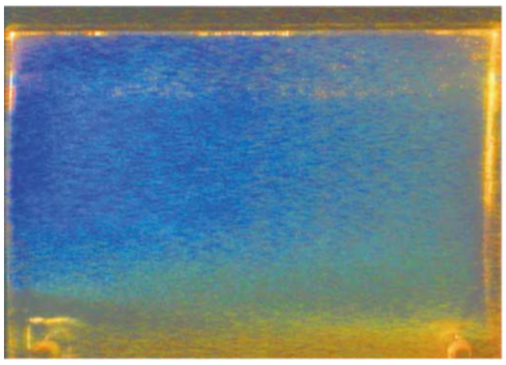

Fig. 7(a)

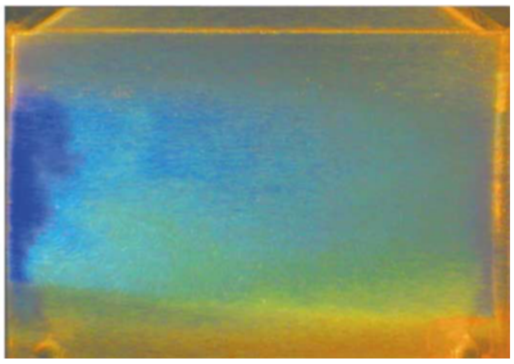

Fig. 7(b)

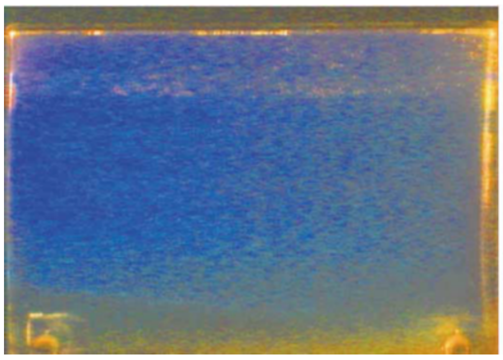

Fig. 8(a)

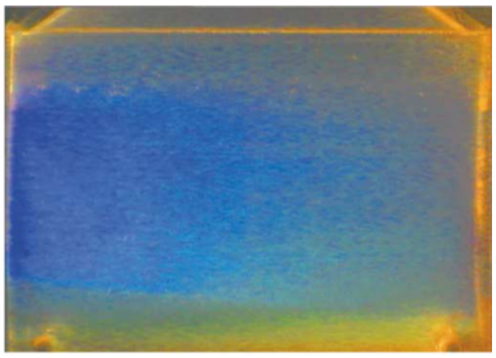

Fig. 8(b)

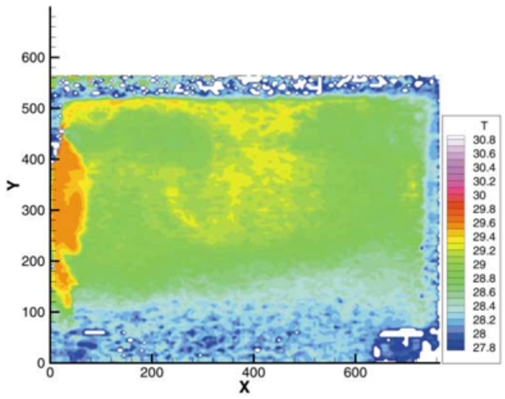

Fig. 9(a)

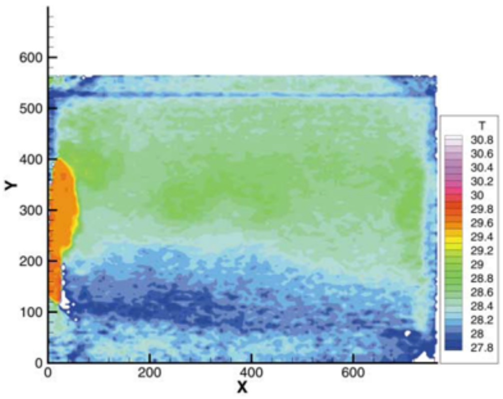

Fig. 9(b)

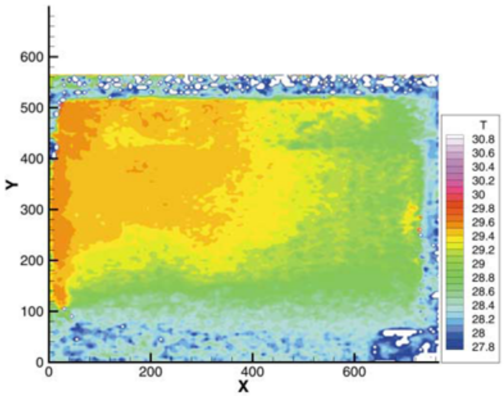

Fig. 10(a)

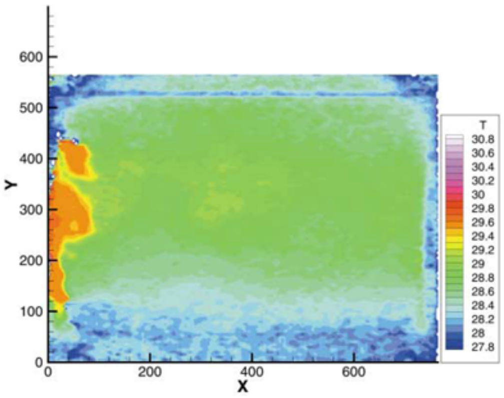

Fig. 10(b)

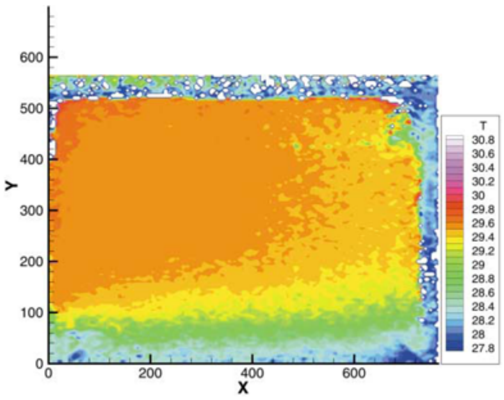

Fig. 11(a)

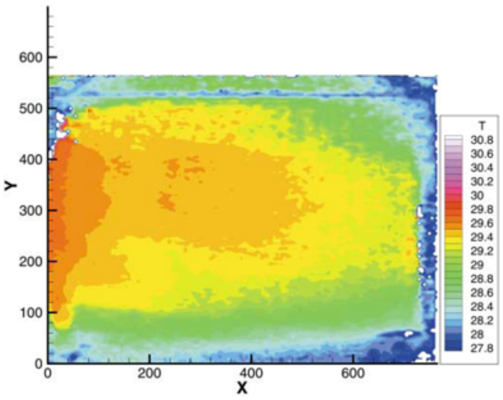

Fig. 11(b)

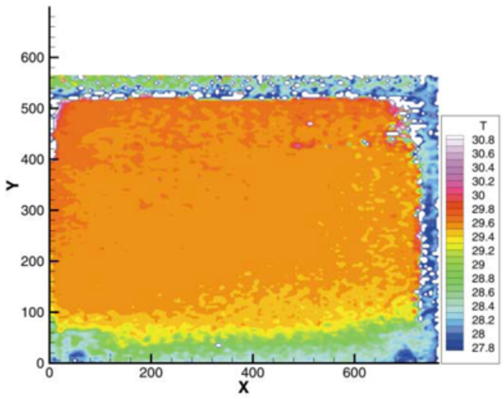

Fig. 12(a)

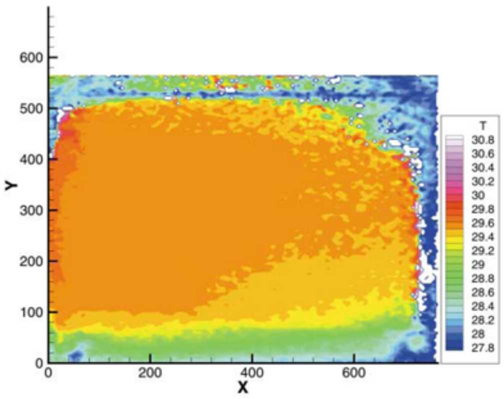

Fig. 12(b)

5. Conclusions

The study has demonstrated the feasibility of making that temperature measurement in water using TLC could be used to predict appropriately scaled temperature distribution in air.

The investigation, however, highlighted a number of restrictions. A large scatter of calibration values due to ADC card that was used for the experiment and the properties of kiral-nematic TLC diminished the precision of calibration. In any follow up study, the quality of the ADC card will be considered and Choresteric TLC will be used. Current work suggests that another possible approach would be to replace TLC particles with particles covered with thermo-sensitive paint (TSP) whose fluorescence level depends on the ambient temperature. In this way the measured parameter becomes primarily colour only eliminating the requirement for intensity measurement.

Modelling requirement discussed fully in the text meant that the temperature variation of 3° K obtained in the experiment with water had to be divided by the temperature scale factor $T_{scale} \approx 4$. Thus a measurable temperature difference for air is less than 1° K. For further investigations TLC with a greater bandwidth will be used.

Due to the small difference in density between TLC and water, TLC may float or drop-out of suspension over longer period and repeated mixing may be required. Mixing can result in concentration non-uniformity so that frequent re-calibration was necessary.

After completion of feasibility tests further investigations for this problem should be carried out, using the same method but more advanced experimental models. A 3D model could be used, including the exact geometry of the building. Windows will be modelled by a change of the thickness of the 'Plexiglas' or the substitution of 'Plexiglas' by materials of different thermal conductivity.

A combination of the TLC method with a Particle Image Velocimetry (PIV) technique would be beneficial since it would allow complementary measurements of the vector.

The method has the potential for the application to other internal convection studies, for instance in automobile interiors.

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References

Daws, L. F., Movement of Air Streams Indoors, (1970), Ministery of Public Building and Works.

Fujisawa, N., Saito, R. and Onuki, S., Calibration Techniques of Liquid Crystal Thermometry and its Application to the Measurement of Temperature Field in a Heater Unit, Proc. 8th International Symposium on Flow Visualization, September 1-4 (1998) (Editors G. M. Carlomagno and I. Grant), paper 222, pp. 222.1-222.8, ISBN 0 9533991 0 9. <http://www.ode-web.demon.co.uk/post-conf-web/flyer.html>

Kowalewski, T. A., Cybulski, A. and Rebow, M., Particle Image Velocimetry and Thermometry in Freezing Water, Proc. 8th International Symposium on Flow Visualization, September 1-4 (1998), (Editors G. M. Carlomagno and I. Grant), paper 24, pp. 24.1-24.8, ISBN 0 9533991 0 9. <http://www.ode-web.demon.co.uk/post-conf-web/flyer.html>

Kutateladze, S. S. and Borishanskii, V. M., A Concise Encyclopaedia of Heat Transfer, (1966), Pergamon Press.

Ohue, H., Kawashima, G. and Yang, W.-J., Visualisation of Cold Thermal Plumes Induced by Rotating Cold Surface, Proc. 8th International Symposium on Flow Visualization, September 1-4 (1998), (Editors G. M. Carlomagno and I. Grant), paper 141, pp. 141.1-141.7, ISBN 0 9533991 0 9. <http://www.ode-web.demon.co.uk/post-conf-web/flyer.html>

Pesko, S., Air Flow Visualization for Wall Paintings in Historic Buildings: Review and Investigation of Potential Methods, Postgraduate Diploma Dissertation, Conservation of Wall Painting Department, Courtauld Institute of Art, University of London, (2000).

Pesko, S. and Pender, R. J., Real Buildings, Real Problems: Visualising Air Movement Around Murals, Proc. 9th International Symposium on Flow Visualization, August 22-25 (2000), (Editors G. M. Carlomagno and I. Grant), paper 243, pp. 277.1-277.11, ISBN 0 9533991 1 7. <http://www.ode-web.demon.co.uk/9misfv>

Press,W.H., Teukolsky, S.A., Vetterling, W. T. and Flannery, B. P., Numerical Recipes in Fortran — The Art of Scientific Computing, Second Edition, (1992), Cambridge University Press.

Raznjevic, K., Handbook of Thermodynamics- Tables and Charts, (1976).

Scholzen, F. and Zuerich, ETH., Luftbewegungen in Rauemen, (1997), HLK.

Thermochromic Liquid Crystals, Product Information of Hallcrest, 1820 - Pickwick Lane, Glenview, Illinois

Vishnevski, E., Rochester Institute of Technology, Department of Computer Science, Internet: http://www.cs.rit.edu/~ncs/color/

Wilcox, A. A., Watson, A. T. and Tatterson, G. B., Colour Temperature Calibrations for Temperature Sensitive Tracer Particles, International Symposium of Physical Numerical Flow Visualisation, Albuquerque, (1985).

Wisniewski, T. S., Kowalewski, T. A. and Rebow, M., Infrared and Liquid Crystal Thermography in Natural Convection, Proc, 8th International Symposium on Flow Visualization, September 1-4 (1998) (Editors G. M. Carlomagno and I. Grant), paper 212, pp. 212.1-212.8, ISBN 0 9533991 0 9. <http://www.ode-web.demon.co.uk/post-conf-web/flyer.html>

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