FLOW VISUALIZATION IV

Proceedings of the Fourth International Symposium on Flow Visualization, August 26–29, 1986, Ecole Nationale Superieure de Techniques Avancées, Paris, France

Edited by

Claude Véret

Office Nationale d'Etude et de Recherche Aérospatiale
Châtillon, France
and
Association Nationale de la Recherche Technique
Paris, France

HEMISPHERE PUBLISHING CORPORATION

A Subsidiary of Harper & Row, Publishers, Inc.

Washington New York London

DISTRIBUTION OUTSIDE NORTH AMERICA

SPRINGER-VERLAG

Berlin Heidelberg New York London Paris Tokyo

SIMULTANEOUS MEASUREMENT OF TEMPERATURE AND VELOCITY FIELDS IN THERMAL CONVECTIVE FLOWS

W.J. Hiller and T.A. Kowalewski*
Max-Planck -Institut fur Stroemungsforschung, Bunsenstrasse 10,
3400 Goettingen, FRG

INTRODUCTION

Thermal convection is an important mechanism of heat and mass transfer in nature and technology. Numerous applications are found in geophysics, astrophysics, meteorology and technology. For example nuclear reactors, energy storage containers or buildings insulation are governed by thermal convective processes. A huge number of numerical calculations is concerned with these complex phenomena. However, quantitative fundamental experiments seem still necessary for better understanding of both the physical phenomena a their numerical simulations.

In the following experiment we present an application of liquid crystals for visualizing both, temperature and velocity fields in thermal convective flows. Such a visualization leads not only to a global picture of the flow configuration but also allows simultaneous and detailed quantitative measurements of temperature and velocity. In our experiment we are concerned with the problem of thermal convection in a cube-shaped cavity where two opposite walls are kept at different temperature while the other four walls are insulated.

DESCRIPTION OF THE METHOD, CALIBRATION

The application of liquid crystals for surface temperature measurements in aerodynamics is well known and has been there developed to an useful experimental technique [1]. Chiral nematic liquid crystals which are used for such a purpose, behave as a multilayered Fabry-Perot interference filter and will selectively reflect incident radiation. Any disturbance of the forces maintaining its internal structure will result into a change in the wavelength of the selective refraction. If this variation of the distance of internal interference layers is due to temperature changes, then the colour of the liquid crystals is a measure of the temperature. This process is reversible and will be used for temperature measurements.

r the practical application the colour play function $\lambda(T)$ gives the wavelength of the selectively reflected light as a function of temperature. This function has been measured at distinct wavelengths for liquid crystals of the type RW 28 and TM 107 used in our experiments (Fig.1). The substances were dispersed into small droplets (typical diameter 10 - 50μm) and suspended in the flow medium. If this selective refraction occurs in the visible light range, then by cooling down the liquid crystals, the colour of the refracted light changes from blue to red. Assuming that the liquid crystals droplets are in perfect thermal equilibrium and have no slip velocity, they also indicate the temperature of the surrounding flow medium and follow the streamlines. Using stroboscopic illumination the flow velocity can be evaluated from the liquid crystal particles displacements. For steady flow, particle traces are identical with streamlines and can be

---

*) On leave from IPPT PAN 00-049 Warszawa, Poland

readily compared with analytical or numerical results for the flow field investigated. The colours of the particles, which for a global view were registered on a photography, were also quantitatively analyzed directly with help of a series of optical interference filters. For a given isotherm (line of constant colour), the exact value of temperature was found with help of the previously obtained calibration curve (Fig.1).

The colour play function λ(T) depends on the angle of observation. This effect causes a broadening of the observed isotherms. The influence of the angle of observation for the geometry of our cavity was tested in the following experimental set up. A He-Ne laser light beam was sent through a cavity filled with a suspension of the liquid crystals in glycerol. The vertical temperature gradient was generated by heating the upper surface. So, a stable and easy to evaluate temperature distribution within the cavity was obtained. The light refracted by the dispersed liquid crystals was collected at a prescribed angle (relative to the incident beam) on a photodiode. The intensity of the refracted light was measured with help of a lock-in amplifier. When the cavity was moved up and down relative to the He-Ne laser beam, the measured light intensity varied and had a sharp maximum at the position related to the selective refraction of the liquid crystals. The position of the maximum, measured for different angles of observations give us the temperature shift due to this angle (Fig.2). This curve can be used for evaluating the accuracy of the temperature measurements due to a finite angle of observation. The slope of the curve in Fig.2 decreases at decreasing wavelength. So, the error in temperature due to a finite aperture angle becomes lower for shorter wavelengths. Hence, making use of Fig.2 which is taken at λ= 633nm, we are able to find the maximum aperture angle for a desired accuracy of the temperature measurements.

The calibration curve of Fig.1 has been obtained for a cavity with a vertical temperature gradient as well. Here, the cavity was illuminated with a white flash light and the colour of the light refracted at 90° was analyzed with help of a series of interference filters. The dots of Fig.1 connected by a continuous line refer to a temperature gradient in the cavity of 0.17 °C/mm and the crosses to a gradient of 0.08 °C/mm . The difference between both curves is probably due to a heat flux through the side walls which,

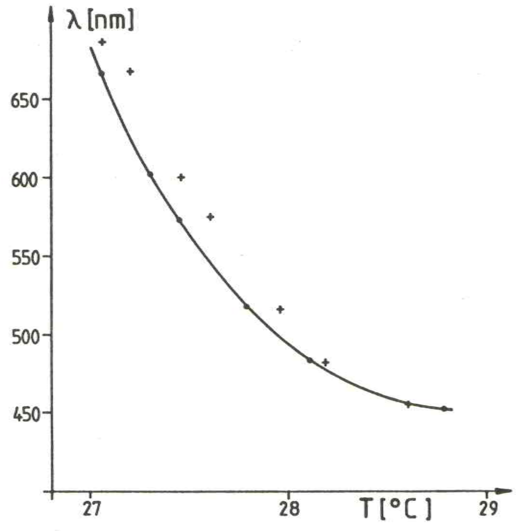


Fig.1 Dependence of the wavelength of the refracted light on the temperature T of the liquid crystals. Observation angle α= 90°.

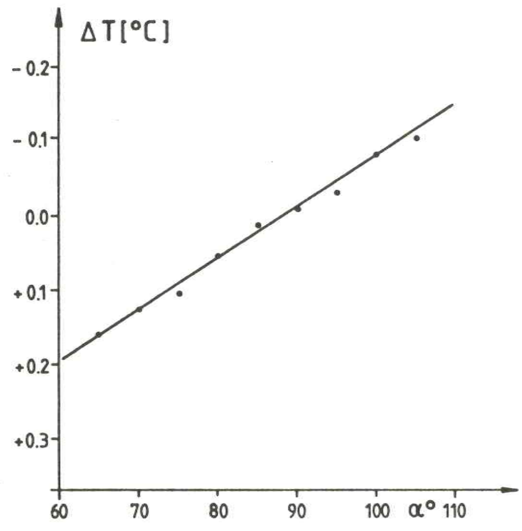


Fig.2 Dependence of the temperature shift ΔT as a function of the observation angle. Illumination by a He-Ne laser.

for the calculating of the temperature gradient, were assumed as ideal insulators. This residual heat flux at the calibration experiments became apparent as a curvature of the isothermal planes in the neighborhood of the sidewalls.

EXPERIMENT

The thermal convective flow was generated in a cube-shaped cavity of 3.8 cm length of side. Two opposite lateral walls of this box were made of metal. They were kept at a prescribed temperature by two Peltier elements. The four other walls, made from 8mm plexiglass, were considered to be thermal insulators (Fig.3). The temperatures of the heated and cooled wall were continuously measured by thermocouples and registered by a Philips multichannel recorder. The temperature fluctuations were below 0.1 °C. The illumination of the flow field was done by a specially adopted photoflash. A cylindrical lens and a diaphragm mounted in front of the discharge tube allowed to obtain a light sheet of 2mm of depth and 50mm of width. The flash lamp was triggered by a personal computer at a prescribed time sequence. Usually five to ten flashes were used to take one photography. The time interval between flashes varied from 1 to 20 sec. To obtain information about the direction of the flow either the first or the last flash of a series has been released at half of the prescribed time interval. On the photo the liquid crystal particles conveyed by the flow appear as a series of coloured and regularly spaced dots. The photos were taken by a 35mm camera with 135 mm lens at an angle of 90° relative to the light sheet. The diaphragm typically used was 5.6, so the angle of observation was less than 3 degrees.

As it is of importance to find out whether the observed flow can be treated as two dimensional, photos were taken at different vertical and horizontal cross sections of the cavity (from ca. 2mm from the front wall in steps of 5mm in the direction to the opposite wall). Also stereoscopic photos of the whole cavity have been taken.

Secondly, as it is also very important to know whether and when the flow is stationary, the time development of the convection pattern has been observed. For this purpose preferably a 16 mm movie camera has been used.

Two main parameters i.e. the Rayleigh number Ra and the Prandtl number Pr characterize convective flows. Several different mixtures of glycerol and water permitted to cover Prandtl number from 5 to $6\cdot 10^3$ and Rayleigh number from 10^4 to $3\cdot 10^7$. The temperature difference between the heated and the cooled wall was varied in the range between $\Delta T = 3°C$ to $\Delta T = 15°C$. The value of the temperature at the walls was chosen so, that the colour play of liquid crystals (27°C - 30°C), was observed at the center of the cavity.

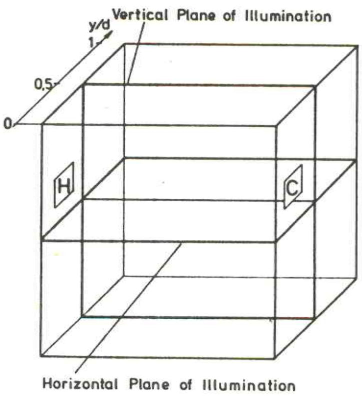


Fig.3 Scheme of the experimental setup. H,C are the heated and cooled walls respectively. Visualization of the flow in the center horizontal plane and in the vertical planes of different distances y/d from the front side.

RESULTS AND DISCUSSION

On Fig.4 examples for the velocity and temperature fields are shown.They are evaluated from the pictures of the cavity filled with pure glycerol. One central vorticity roll and a reverse temperature gradient characterize this type of convection. Similar graphs were obtained as a result of various two dimensional numerical models [2,3]. A careful investigation made by the above visualization method shows that even this "classical" convection can not be treated as two dimensional. The observations at different vertical cross sections of the cavity showed that approaching the cavity wall both the flow field and the isotherms drastically change their shape (Fig.5). The visualization in the horizontal cross section indicates very clearly the third dimension of the convection (Fig.6).

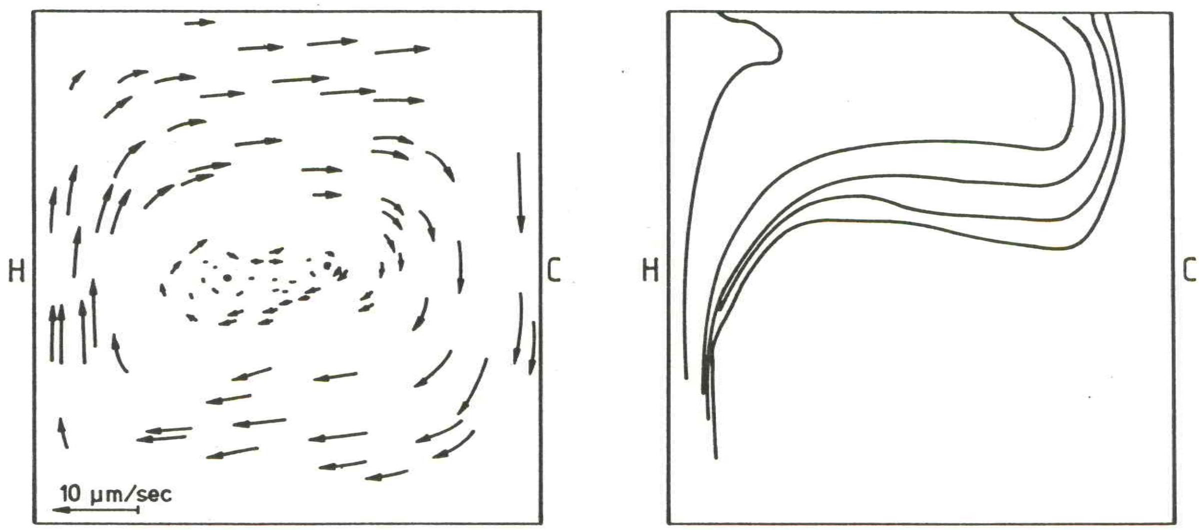


Fig.4 Convection velocity (a) and temperature field (b) for Pr= $6\cdot10^3$, Ra= $3\cdot10^4$, at the center of the cavity (y/d =0.5).

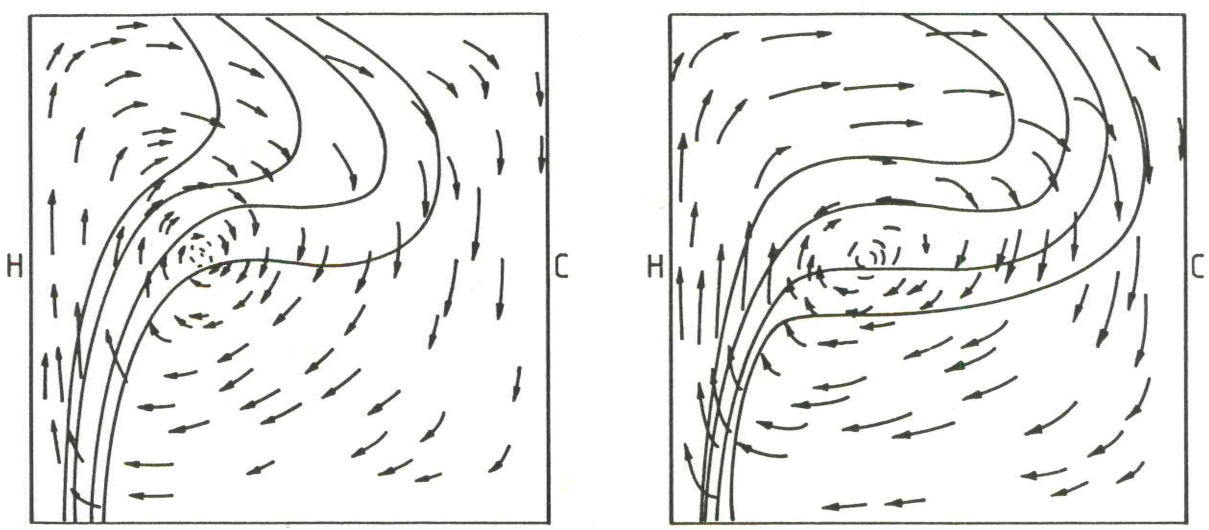


Fig.5 Convection velocity and isotherms for Pr = $6\cdot10^3$, Ra= $2\cdot10^4$.
(a)- y/d= 0.05, (b)- y/d= 0.2.

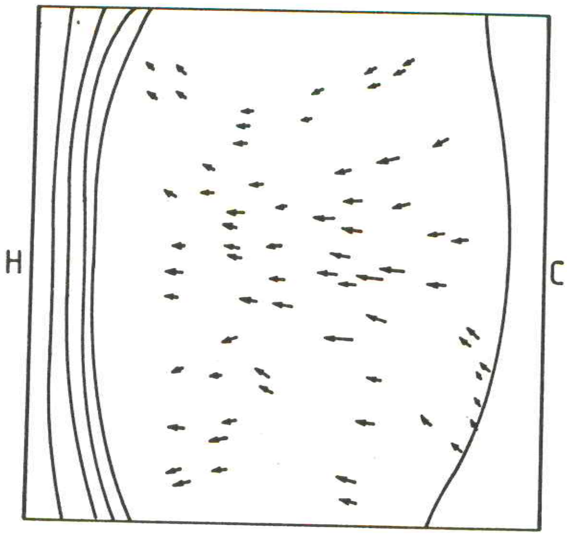
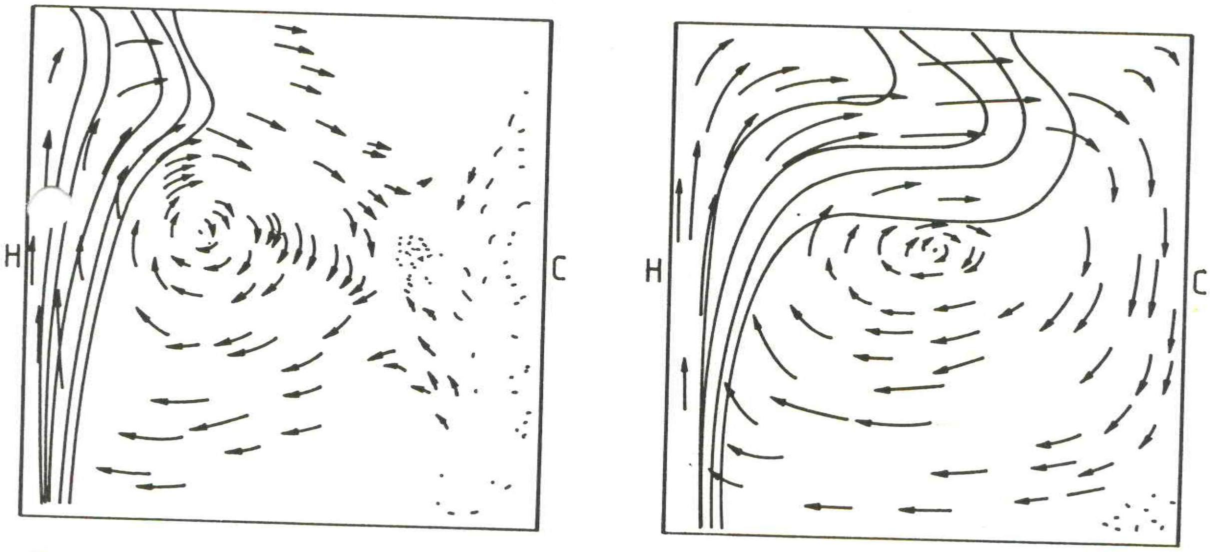


Fig.6 Convection velocity and isotherms for Pr= $6\cdot10^3$, Ra= $3\cdot10^4$, horizontal cross section at the midplane of the cavity.

The lower the Prandtl number and the higher the Rayleigh number, the flow bec[...]es more and more complicated. Consequently, secondary rolls are formed and their centers are shifted towards the side walls. However, the temperature field changes very little. For Ra = 10^7 and Pr = 5 the three-dimensional character of the convection becomes well visible, even within the midplane of the cavity. The flow field between the rolls becomes very complicated and is rather of spiraloidal character. This type of circulation was predicted by Mallinson and de Vahl Davis [4] in their numerical solutions for three-dimensional convection. However, quantitative comparison of their results is not possible.

The time development observed for the thermal convection in our cavity surprisingly shows that even for such a viscous and poorly heat conducting



ig.7 Convection velocity and isotherms for Pr= $6\cdot10^3$,Ra= $2\cdot10^4$,y/d= 0.5. ime development (a) - 2 min., (b) - 8 min. after applying temperature radient.

liquid as glycerol, the flow and temperature field are fully developed within 20-30 minutes. It is interesting to observe how the initially horizontal temperature gradient is convected into vertical one by an immediately developed vortex flow (Fig.7).

SUMMARY

The visualization of the velocity and temperature field by liquid crystals seems to become a promising tool. This is especially true for those cases where nonstationary or complex temperature fields cannot be resolved by the traditional thermocouples.
The high intensity of the light refracted at the sensitive wavelength band has additional advantage in visualizing the interior regions of the flow. When observation takes place through a thick layer of fluid, the liquid crystal particles outside the field of illumination are quite transparent and optically nonactive for a secondary illumination in the direction of observation.
However, it must be mentioned that the preparation and the preservation of the liquid crystal particles is tedious and possible only for a liquids not destroying their optical properties. For example, most of the alcohols and oils were found useless as a carrier fluid. In such cases encapsulated liquid crystals (commercially available) are advisable.

REFERENCES

1. Schoeler H., The Measurement of Heat Transfer and Temperature Distributions in Hypersonic Testing, Von Karman Institute for Fluid Dynamics, Lecture Series 1, Hypersonic Aerothermodynamics ,Febr. 6-10,1984.

2. de Vahl Davis G., Laminar Natural Convection in an Enclosed Rectangular Cavity, Int. J. Heat Mass Transfer, vol.11, pp.1675-1693, 1968.

3. Phillips T.N., Natural Convection in an Enclosed Cavity, J. of Comp. Phys., vol.54, pp.365-381, 1984.

4. Mallinson G.D., de Vahl Davis G., Three-dimensional Natural Convection in a Box, Numerical Study, J.Fluid Mech.,vol.83, pp.1-31, 1977.