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VISUALIZATION OF 3-D NATURAL CONVECTION - COMPARISON WITH NUMERICAL RESULTS.

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SUMMARY

The convective flow inside a box with two heated side-walls is investigated experimentally and numerically in the Rayleigh-number range 20000<Ra<100 000. The flow structures observed are strongly 3-dimensional in the entire Rayleigh-number range. To get reliable results on the shape of the streamlines by numerical simulation a minimum mesh size of 51x51x51 is necessary for Ra=80000. The numerical solutions depend sensitively on the thermal properties of the remaining four transparent walls through which the flow is observed. Small deviations from ideal adiabatic walls result in strong changes of the structure of the flow field.

INTRODUCTION

Among the transport mechanisms for heat and mass thermal convective flows play a dominant role. With the exception of some highly symmetric configurations these flows are in general of intrinsic 3-D character, but due to the expenditure of time and to difficulties connected with the experimental techniques and the numerical modeling they have been treated in the past mainly with 2-D methods. On the other hand, it is commonly accepted that a general conception of such flows and the development of their topological structure can only be provided by a full 3-D description.

Former experiments on natural convection in a cube shaped box with two differentially heated side-walls (Fig. 2) showed that from the very beginning at low Ra-numbers 3-D effects completely change the character of the flow (Hiller et al. 1989). The simple vortex roll, well known from the corresponding 2-D case, turns into a set of two spirals where the flow medium in the neighbourhood of the axes runs from the corresponding side walls to the centre symmetry plane of the cube whereas in the outer regions of the spirals the direction of the flow is reversed. This process is accompanied by the formation of additional singular points. While for low values of Ra the flow structure could be modelled quite well by numerical calculations assuming adiabatic side walls, first severe discrepancies became apparent for Ra $\sim$ 40000. In the experiments the vortex splits up into two vortices in the neighbourhood of the centre symmetry plane. It seems as if the outer region of the first vortex twists off and forms a new spiral, while in the neighbourhood of the corresponding side-walls the single vortex structure remains unchanged - a configuration that up to then was not known and could not be modelled numerically under the assumption of adiabatic walls. It soon became obvious that the flow structure depends very sensitively on the thermal properties of the remaining four side-walls which in the above case were made from plexiglas to provide optical access to the cavity. Even though plexiglas is a very good insulator and therefore the resulting velocity field undergoes only small modifications, the streamlines, however, may react extremely sensitive on such changes as they are integrals of the velocity field and thus systematic deviations are enhanced. Especially in 3-D fields where streamlines generally will not be closed and mixing may occur even for stationary flows, significant changes of the flow structure are to be expected. So, it is not surprising that first numerical calculations with a temptative heat flux through the originally adiabatic side-walls indeed showed the splitting of the vortex but resulted into an adverse axial velocity direction of one of the vortices compared with the experimental findings.

To solve this problem for walls of non-zero thickness and of finite non-zero thermal properties one would have to treat the enclosure together with the flow numerically. For the outer surfaces of the enclosure one has to pose new boundary conditions which of course would be simpler than for the inner ones. However, the computing problems seem to become so complicated that a more pragmatical approach is preferred at the moment. Its main idea consists in measuring the temperature distribution of the inner walls of the cavity, adopt them in some way to the numerical calculations and finally to compare the observed with the calculated streamlines.

EXPERIMENTAL

The main components of the experimental setup are displayed schematically in Fig. 1. The cube shaped box of 50 mm length of inner side, the CCD-camera and the light source are mounted together on an angular frame. The frame can be tilted around a horizontal axis by 90^0 to observe horizontal and vertical cross-sections without additional adjustment of the optics. The two vertical side walls of the box (Fig. 2) that are always vertical are made of black anodized metal. Their temperatures are maintained by thermostats within 0.1 ^{0}C of the prescribed values. The other four walls are made from 8 mm plexiglas. A 2 mm thick light sheet generated by a xenon discharge tube is used to illuminate square cross-sections of the enclosure. Visualization of the flow is performed by special tracers suspended in the flow medium. They are observed at right angles to the light sheet (dark field mode) by a 3 chip CCD RGB-camera. As a flow medium glycerol (Prandtl-number Pr=6300) and glycerol-water mixtures are used. The images captured by the RGB-camera are digitized by image processing boards and stored for further evaluation.

Liquid-Crystal-Technique. To observe simultaneously particle displacement and temperature small ($\phi \sim 50$ µm) uncoated thermochromic liquid crystal (LC) droplets are suspended in the flow medium. Depending on their temperature, the optical reflectivity of the LC with respect to the wavelength changes. The temperature span (colour play) necessary to cover the visible region depends on the chemical formulation of the substance and on the angle of observation. In the experiments described here, the colour

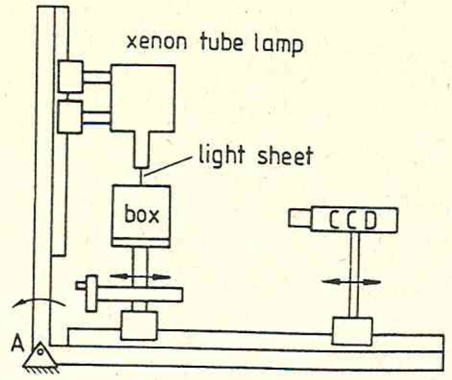

Fig. 1: Scheme of the experimental set-up. Adjustment of the box and of the CCD-camera and the release of the light flashes from the xenon discharge lamp is controlled by a computer.

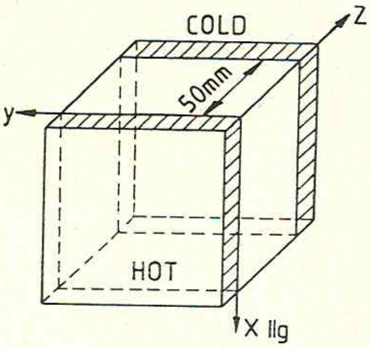

Fig. 2: The cube shaped box. The x-axis is parallel to the gravity vector g. The heated and cooled side walls (hatched) are made from metal the other ones from 8 mm plexiglass.

play amounts to approx. 3 ^oC if the LC tracers are observed at 90^o with respect to the illuminating light beam and to approx. 6 ^oC when viewed at an angle of 180^o. The small angle is chosen for the visualization of the tracers inside the box, whereas the large angle is especially suited for wall temperature measurements. A detailed description of this technique may be found in (Hiller et al. 1988). To observe the temperature on the inner surfaces of the box the LC tracers are deposited as isolated droplets, a continuous layer would be crimpled by the combined action of interface tension and shear stress.

To evaluate the temperature from the colour images captured by the CCD-camera, the hue of the colour that is a single valued parameter is extracted from the intensities of the red, green and blue channel, respectively. The method we apply is very similar to that described by Hirsch et al. (1988). The dependence of the hue from the temperature of the LC substance is gauged experimentally at similar conditions like in the experiment. The graph in Fig. 3 shows a typical curve for an observation angle of 180^o.

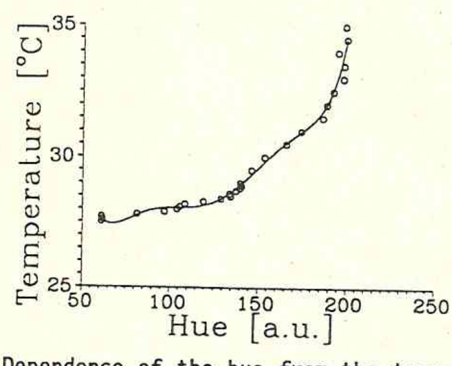

Fig. 3: Dependence of the hue from the temperature of the LC tracer measured at an observation angle of 180^o. Hue for some characteristic colours: 42-red; 84-yellow; 126-green; 168-bluish green; 210-blue.

The evaluation of the velocity in the plane of observation from the displacements of the particle images is performed by standard methods.

3-D Visualization. At increasing Rayleigh-number the flow becomes more and more complex, and the description of its topoplogical structure only from the knowledge of particle traces observed in plane cross-sections may lead to erroneous conclusions. These difficulties can be reduced by observing the entire field of flow simultaneously from two directions. For the case of the cube, the natural way is to look perpendicular through two adjacent walls (e.g. z,x- and y,z-planes) into the channel. The particles are observed against a bright background so that their images appear as dark spots. If there are only a few particles suspended in the flow medium corresponding particle images are detected fully automatically by image evaluating software programs (Bartels-Lehnhoff 1991). As a result, sequences of the particle location in physical space and time are obtained. Colours of the LC cannot be observed by this method.

For the representation and interpretation of the sequences as well as for comparison with numerically calculated values, a display program developed by BROSA GMBH, Amöneburg,FRG for multidimensional variables is applied. It represents the time sequences together with the corresponding 3-D rectangular coordinate system in perspective view on a graphic video screen. Since the angle of observation can be changed quickly the structure of a particle path in 3D space and time is easily established and may be compared in a similar manner to calculated values. As the particles also carry a time mark the display program is able to connect successive locations of a particle by a straight line so that the path of a tracer-particle becomes visible. Without this facility it would be nearly impossible either to revise the measured values or to compare them with the calculated particle traces.

NUMERICAL MODELING

The experiments are accompanied by a 3-D numerical study. This involves the solution of finite difference approximations to the equations of motion and energy. The computer code used assumes the thermal conductivity, viscosity and specific heat of the fluid to be constant and makes use of the Boussinesq approximation (constant density except in the buoyancy term). A detailed description of these equations that are well-known can be found in (Mallinson, de Vahl Davis 1977, de Vahl Davis 1982). The solutions are calculated on a uniform 51 x 51 x 51 up to 71 x 71 x 71 mesh.

The thermal boundary conditions of the code used allow the imposition of arbitrary temperature, specified heat flux or specified heat transfer conditions on each of the six sides of the box. The two heated side walls are assumed to be isothermal. For the other four walls made from plexiglass the boundary conditions are selected in two ways. At present, the heat flux is adjusted in a try and error mode to get best coincidence with the structures observed. The second method prescribes the wall temperature distribution which is taken from the experimental measurements. It is the actual aim of the present work and will become effective in the near future. Hereby, we hopefully expect to get relevant results also with respect to the assumption of constant material properties.

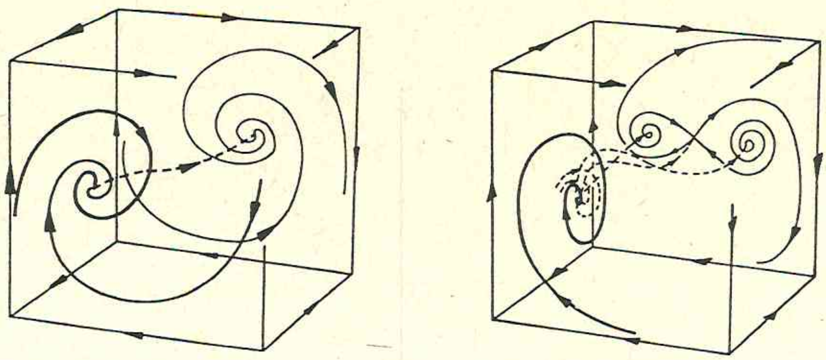

Fig. 4: Topological structure of the flow for Ra=20000 (left) and Ra=80000 (right). Only the front half of the cube is displayed. The left side-wall is heated and the right one cooled. The arrows indicate the direction of the streamlines.

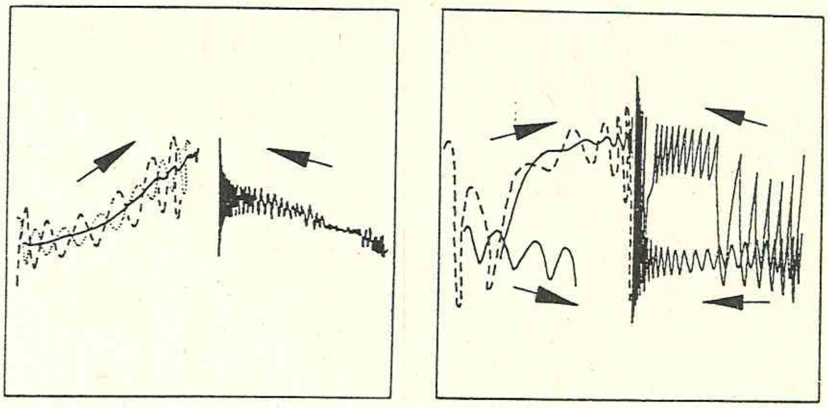

Fig. 5: Streamlines in the spiral core region seen from above in an y,z-plane for Ra=20000 (left) and Ra=80000 (right). Left half of the figures - copied from photographs, right half - numerical simulation.

RESULTS AND CONCLUSIONS

To facilitate the understanding of the problems and to get a better impression of the object investigated, a perspective view of the topological structure of the flow field for the Rayleigh-numbers Ra=20000 and 80000 is displayed in Fig. 4. The left side of the cube is heated and the right one cooled by which a clockwise rotation in the flow medium (glycerol) is induced. Due to the presence of the front and back walls secondary axial flow components are excited that lead to the onset of spiralling motion. For completion, a top view of the fluid motion in the neighbourhood of the axes of the spirals extracted both, from measurements and numerical modeling is added (Fig. 5). For Ra=20000 the centre region of the spiral axis is shifted towards the cold wall, an 3-D effect that also is modeled quite satisfactory by the numerics under the assumption of the above mentioned mean heat flux through the plexiglass walls. First serious difficulties arise at Ra>40000, when the single vortex roll splits up, a process that could not be simulated at all by the assumption of adiabatic walls, and where for the tentative inclusion of a mean heat flux a splitting appeared, however, an adverse axial velocity component in the vortex-branch close to the heated wall shows up.

To solve this problem an extensive numerical study was commenced. For the calculation scheme, the Boussinesq approximation with constant material properties was used. In a first step, it was tested what mesh-size is necessary to get mesh independent solutions for the streamlines irrespective of the strict validity of the boundary conditions assumed. From these numerical simulations it was concluded that for Ra=80000 a uniform mesh of at least 51 x 51 x 51 is necessary. In contrast to the velocity field the shape of the streamlines reacts very sensitive. From this it can be concluded that probably most of the calculations performed on a coarser grid will give erroneous results, and that for increasing Ra-number where flow structures will become finer also the mesh-size of the grid has to be reduced accordingly. These numerical experiments also served to give a survey on the development of the topological structures by systematically changing the boundary conditions. Among these, flow field configurations have been encountered that describe the topological structure of the vortex splitting and the axial motion in accordance with the experimental findings (Fig. 5). For this configuration, the corresponding calculated and measured isotherms on the top and front walls are shown additionally in Figs. 6, 7 . Like in the experiments observed, the isotherms on the top lid (Fig. 6) are curved back into the direction of the heated wall in the neighbourhood of the edge of the front and back walls, respectively. This is due to the combined action of heat flux into the walls and boundary layer. The same effect prevents also the formation of a negative slope of the isotherms on the side walls (Fig. 7). Therefore only one vortex roll is to be expected in contrast to the mid-plane where the slope may take negative values (Mallinson, de Vahl Davis, 1977). On the other hand serious differences between the calculated and measured isotherms remain. The experimentally measured wall temperature distribution in the vicinity of the heated wall is in both cases nearly flat in contrast to the calculations. This

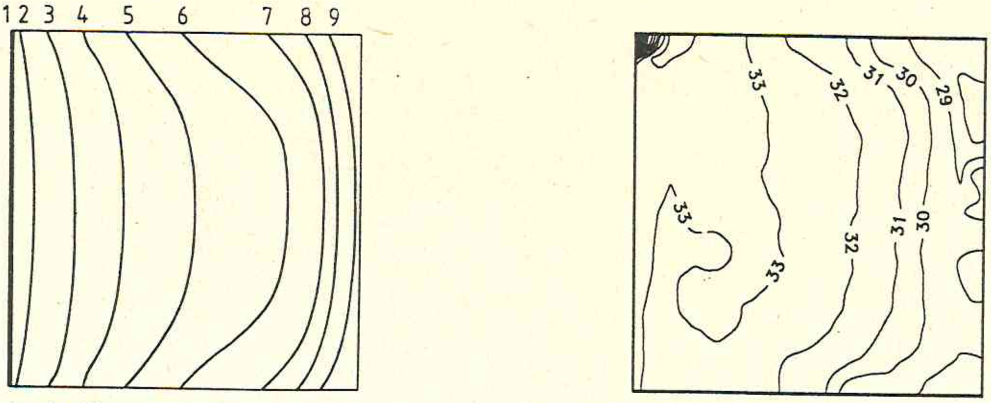

Fig. 6: Isotherms on the top (y,z) wall for Ra=80000. The temperature difference between the hot and the cold wall amounts to 15°C. Left figure: Results from numerical calculation with a heat flux through the plexiglass walls. Right figure: Isotherms measured by the LC-method. The temperature on the isotherms decreases in steps of 1.54 °C at increasing index. Mesh-size: 51 x 51 x 51.

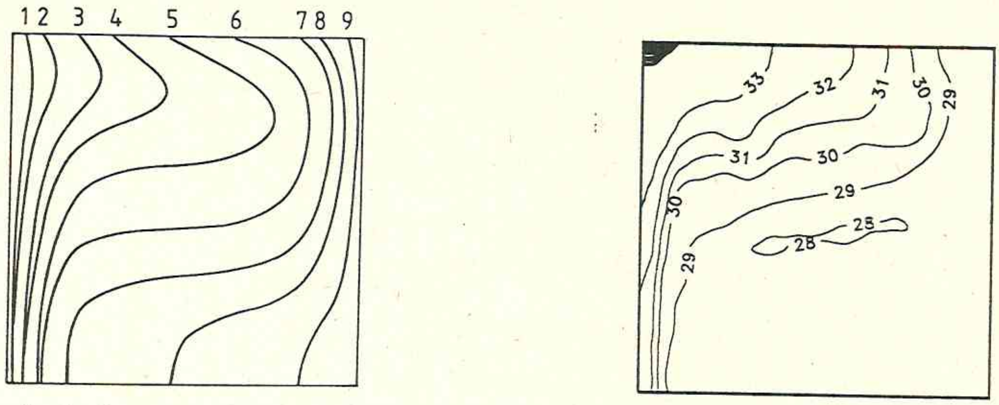

Fig. 7: Isotherms on the front (z,x) wall for the same configuration like in Fig. 6.

discrepancy is presumably due to the assumption of a mean constant heat flux into the plexiglass walls. Even though the accuracy of the temperature measurments by the LC-method may not be very high, it seems quite sure that also the calculated temperature difference for the top lid is too large. Finally, it is maybe worth to remark that the unsymmetry of the lateral isotherms with respect to the centre point of the plane -constant material properties of the flow medium are assumed- is a consequence of the different fluxes to the plexiglass walls.
In the experiments the heat flux from the flow medium into the walls partly leaves the system but partly -by heat conduction along the walls- may return back into the flow medium, since the walls are not infinitely thin. A more detailed discussion would afford an appropiate modelling of the wall together with the flow regime. Instead of doing this, we will prescribe the measured temperature distribution as boundary conditions for the numerical calculations and compare the resulting flow structure with the experimental results. From these we expect to get a useful answer to the question how good the experimentally observed structures can be modeled and also how far the Boussinesq approximation holds.

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