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Free surface natural convection in differetially heated rectangular cavity.

T. A. Kowalewski, A. Cybulski
Polish Academy of Sciences, IPPT PAN, PL 00-049 Warszawa, Poland
G. de Vahl Davis, E. Leonardi
The University of New South Wales, Sydney, 2052 Australia

Extended Summary

The aim of this investigation is to elucidate both experimentally and numerically the transient and steady state natural convective flow at a free surface. The problem is of special interest under low-gravity conditions, when thermocapillary flow plays a triggering role. However, it seems useful to understand the main features of the free-surface flow under on Earth conditions first.

The experiments are performed for a differentially heated cube shaped cavity filled with water-glycerin solutions. Only 90% of the cavity height is filled, leaving small gap of air between its top wall and the fluid surface. The motion is driven by a sudden temperature difference $T_h - T_c$ applied to two opposite metal side walls of the cavity. The other walls through which the flow is observed are made of plexiglas, and even though their heat conductivity is quite small they cannot be assumed to be ideally adiabatic. To get evidence of how the free surface affects the flow structure, the parallel experiments are performed where the upper part of the cavity is closed by an additional plexiglas plate, thus preserving the rectangular geometry of the flow domain.

The basic dimensionless characteristic parameters defining the problem are, the Rayleigh number

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

and the Prandtl number

$$Pr = \frac{\nu}{\kappa} \ . \tag{2}$$

Accounting for the effects of surface tension σ at the free surface two additional non-dimensional numbers characterise the problem, the Marangoni number

$$Ma = |\frac{\partial\sigma}{\partial T}|\frac{(T_h - T_c)L}{\kappa\nu\varrho}, \tag{3}$$

and the Bond number:

$$Bo = \frac{g\varrho L^2}{\sigma}. \tag{4}$$

In the above definitions g, L, κ, β, ν, ϱ denote respectively the gravitational acceleration, the cavity length, the thermal diffusivity, the coefficient of thermal expansion, the kinematic viscosity and the density.

The experiments are performed at the Rayleigh number of $22000 - 395000$ and the Prandtl number of $752 - 8900$, for the cavity of $5cm$ side length. The temperature difference applied is 3^oC or 5^oC (± 0.05). The Bond and Marangoni numbers are 492 and $99 - 2060$.

Selected cross sections of the flow domain are illuminated by light sheet and observed by a high resolution CCD colour camera connected to a three-channel frame grabber. The computer controlled system with step motors allows automatic scanning of the whole flow domain, permitting the collection of a 3-D picture of the flow within a short time. For the flow visualization the seeding with thermochromic liquid crystals is used. This allows instantaneous measurement of the velocity and temperature flow maps for two dimensional cross-sections of the cavity. Two digital methods employing Particle Image Velocimetry and Particle Image Thermometry techniques are used for this purpose[1]. To get better view of the flow structure a long series of B & W images are also accumulated. Afterwards the pre-processed images are superimposed to produce particle tracks.

The experiments performed for the stationary case reveal a strongly three-dimensional recirculating flow transporting fluid from the hot to the cold side, with one or two toroidal structures running across, back and forth between the side walls and centre of the cavity.

The free surface evidently deforms these structures increasing the hot-cold side asymmetry of the flow. Large distinctions between free surface and solid top wall conditions appear during the transient process, when flow starts from rest. In the first case the flow stratification is seen, with relatively strong recirculation rolls close to corners between the bottom and isothermal walls. Once the flow is fully developed, there is a clearly visible flow recirculation directly at the surface. There the flow seems to be de-coupled from the lower “regular” circulation pattern. Whereas the flow along the central part of the surface plane is directed towards the cold wall, reversal flow appears along the side walls (Figure 1).

These experimental evidences are investigated numerically. The calculations are performed using a finite difference vorticity-vector potential formulation of the Navier-Stokes and energy equations using a modified version of the 3-D numerical code FRECON3D (UNSW CFD Group). This relatively robust, false transient solver allows quick generation of the steady state solutions, ideal for parametric studies like the one described. Its modified version includes thermal variation of main fluid properties and incorporates heat conductivity of the closing walls allowing flexible imposition of experimental flow conditions.

All boundaries of the enclosure are assumed to be solid, impermeable and at rest setting all three velocity components to null. For the free surface case the no slip conditions at the top boundary are removed. Hence, the velocity component normal to the top surface and the normal derivatives of both remaining velocity components are set to null. Solutions were obtained using a 41^3 uniform mesh.

The overall agreement between calculated and measured general flow characteristics is satisfactory. The temperature and velocity fields are numerically well reproduced for both free surface and solid top wall conditions. However, the observed recirculating flow at the surface is not found at the time. Neither relatively strong effects of the variable fluid viscosity, nor non-adiabatic thermal boundary conditions produce observed recirculating flow at the surface.

Due to the strong gravitational effects it is believed that incorporation of the thermocapillary effects will be only unnecessary complication of the numerical model. Hence, we assume flat undeformed free surface and absence of thermocapillary flow. At the present stage it seems necessary to verify above assumptions. This work is still in progress. Several possible hypotheses for the appearance of the surface flow will be discussed and their eventual numerical verification

[1] Hiller W.J., Koch St., Kowalewski T.A., Stella F., Onset of natural convection in a cube; Int. J. Heat Mass Transfer **36** (1993), 3251–3263.

presented. These are:
1. Flow stratification induced by variable viscosity.
2. Surface curvature and effects of gravitational counter flow at the surface.
3. Thermocapillary flow.
4. Physico-Chemical process: yield stress due to the layer of less mobile glycerin molecules fixed at the surface.
5. Dynamic and thermal coupling between air gap and underneath fluid.

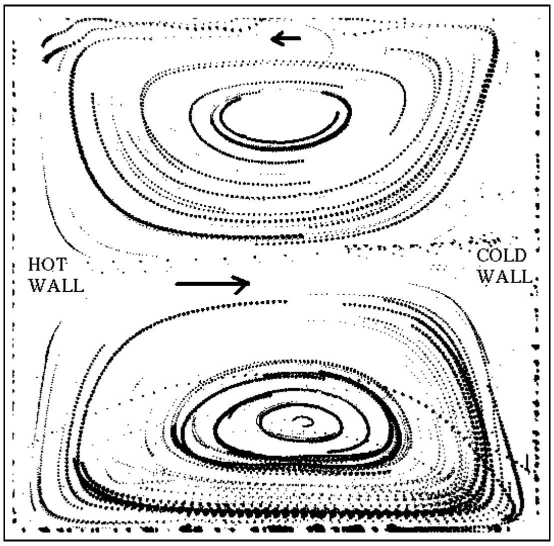

Figure 1: Flow pattern observed at the top surface of the fluid. Ra = 395000, temperature difference 5^oC. 99-fold exposure at 20s intervals