

Experimental and numerical investigations of buoyancy driven instability in a vertical cylinder

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Natural convection of water is investigated experimentally and numerically in a vertical cylinder. The flow is driven by a vertical temperature difference between a cooled metal lid and an external bath heating remaining glass walls. The onset of convection flow exhibits several instabilities with a semi-oscillatory transition to a regular recirculation pattern characterized by the cold fluid stream flowing down along the axis. In spite of an axisymmetric geometry, the flow exhibits an interesting three-dimensional pattern, splitting in the azimuthal direction into a several regular cells. This phenomenon is well observed as regular temperature variations under the lid, which are visualized using thermochromic liquid crystals. For water freezing from the lid, the phenomenon becomes responsible for radial wavy deformations of the ice surface. Numerical simulations performed using a three-dimensional finite-volume solver confirm the main features of the experimental findings, i.e. transient instabilities of the flow onset and the steady flow structure partitioned in the azimuthal direction.

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Convective flows in an axisymmetric geometry are common for many technological processes and are widely used as experimental and numerical models. It is often assumed that the 2π -periodicity of axisymmetric flow permits the complex 3D problem to be reduced to a simpler case of so-called 2.5-D axisymmetric solutions. However, even for the ideally axisymmetric case initial disturbances may lead to the flow instabilities and development of three-dimensional flow structures. In the following an example of the axisymmetry-breaking bifurcation of natural convective flow in a vertical cylinder is described. Both experimental and numerical investigations confirm existence of steady pattern of the azimuthal structures.

We consider convective flow of water in a vertical glass cylinder immersed in a bath of constant temperature. The top metal wall of the cylinder is isothermal at a low temperature T_c . The side wall and bottom are non-adiabatic, allowing a heat flux to cross from the external fluid which is kept at a temperature T_h . Due to forced convection in the bath, it could be assumed that the temperature of the external surfaces of the cylinder is close to the bath temperature. The temperature field at the inner surfaces of the walls adjusts itself depending on both the flow inside the cylinder and the heat flux through and along the walls. To some extent the problem investigated here exhibits similarities to the Czochralski crystal growth configuration.

The flow is driven by the temperature difference $\Delta T = T_h - T_c$. The cavity has 37mm inner diameter and 41mm inner height. Natural convection is studied for the lid temperature varied from 6-20°C and ΔT range of 4-10°C. This covers the transition from steady laminar flow at a lower Rayleigh number ($Ra = 3 \cdot 10^5$) to an unsteady, pulsating regime ($Ra > 10^6$). By lowering the lid temperature to -10°C the effect of solidification was investigated with ice front growing down from the lid.

Flow observations were made at several vertical and horizontal cross-sections of the cavity by applying the 3CCD color camera, frame grabber and a system of stepping motors used to set a light sheet for illuminating the flow. Particle tracking and detailed measurements of the temperature and velocity fields were employed to collect transient data about the flow pattern. The technique applied, called Particle Image Velocimetry and Thermometry, is based on measurements of color and displacement of thermochromic liquid crystals used as tracers [1].

The onset of convection exhibits strong instability. The flow starts, when an initial cold thermal boundary layer at the lid becomes unstable, breaking down into several plums falling down along the side wall. These plums in turn generate several recirculating zones, transporting heat and vorticity from the side wall to the center. This configuration is unstable. After 3-5 minutes flow reversal occurs and several strongly asymmetric flow structures are formed. A final configuration with a single cold jet along the cavity axis and a reverse flow along the side wall is established. At the lower Rayleigh number range this pattern is stable, however not necessarily axisymmetric.

It was found that at a certain set of parameters, the temperature field measured in the fluid in a horizontal cross-section slightly below the top shows a regular star-like pattern with 16-18 radial structures. It indicates presence of an azimuthal instability splitting the flow along the circumference into several wedge-like cells (Fig.1a). It is interesting to note that these structures remain even when the phase change takes place, creating a radial grooving in the ice surface (Fig.1b).

Detailed observations of particle tracers showed pairs of counter-rotating cells forming along the lid circumference (Fig. 2). These cells are, in fact, cross-sections of spirals transporting hot fluid from the side wall towards the lid center. It is believed that the thin thermal boundary layer under the lid is responsible for the Rayleigh-Benard like instability, which in turn leads to the formation of small convection cells along the circumference. The temperature gradient determines the height of this boundary layer. The height defines the size of the convection cells, hence the number of structures, which fits to the circumferential length.

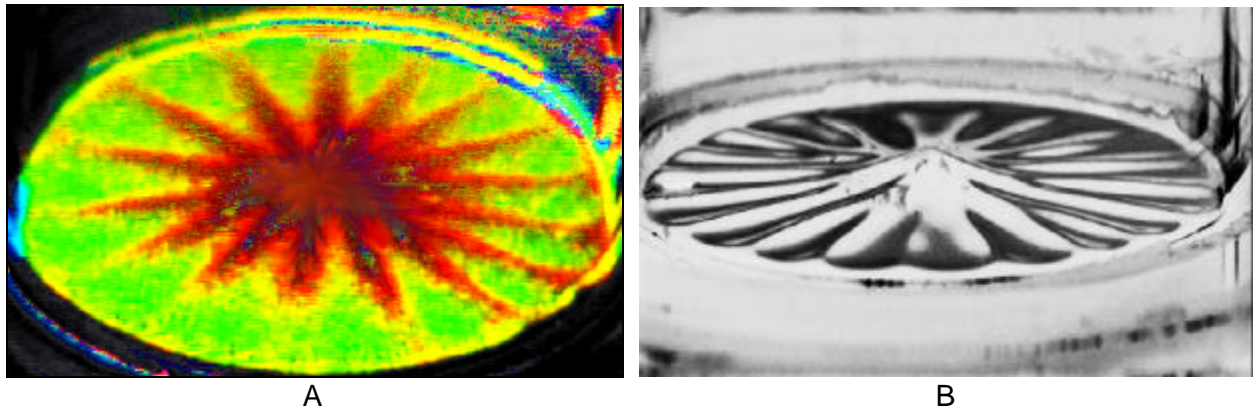


Fig. 1 (a)- temperature distribution under cooled lid visualized by liquid crystals (red color indicates lower temperature); (b)- ice structure appearing under the lid; (upside down view).

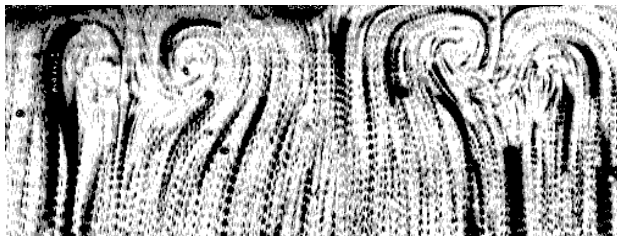


Fig. 2 Particle tracks observed at the edge of the lid. Pairs of counter-rotating rolls are cross-sections of small spirals running radially from the wall to the lid axis; displayed section of 15mm width.

Numerical simulations of the problem were performed using a finite volume, primitive variables formulation of the Navier-Stokes and energy equations using a fully 3D cylindrical system of coordinates [3]. It was found that proper modeling of the thermal boundary conditions at the side and bottom walls has a triggering effect on the flow structure formed. Hence, a coupled solid-fluid heat conduction problem for the flow bounding walls was solved together with the 3-D Navier-Stokes equations. When transient properties of the flow were investigated, initial disturbances of the boundary conditions were applied to speed up development of the asymmetric flow modes.

The numerical results obtained confirm fully the experimental findings. The initial instability and flow reversal of the flow exhibit the same pattern development that was observed in the experiment. These will be demonstrated by comparing animated computer simulations with the liquid crystal visualizations of the physical flow. The characteristic star-like structure emerges at the horizontal plane under the lid when the final steady flow configuration is reached. The “particle tracks” obtained from the computational flow fields indicate the presence of the spiraling flow structures under the lid. This finding supports our hypothesis that the instability is of Rayleigh-Benard type.

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