LA-UR- 97-3463

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

CONF-970851--

TITLE: REGULAR AND CHAOTIC FLOW PATTERNS UPON IMPULSIVE SPIN-UP OF A RAYLEIGH-BENARD CONVECTION CELL

AUTHOR(S): Peter Vorobieff, CNLS,DX, MST, and T-Division
Robert E. Ecke, MST

SUBMITTED TO Proceedings of 4th Experimental Chaos Conference at Boca Raton, FL - August 5, 1997 to august 9, 1997

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED



Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

## DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

## DISCLAIMER

# REGULAR AND CHAOTIC FLOW PATTERNS UPON IMPULSIVE SPIN-UP OF A RAYLEIGH-BÉNARD CONVECTION CELL

PETER VOROBIEFF and ROBERT E. ECKE
*Center for Nonlinear Studies and*
*Condensed Matter and Thermal Physics Group*
*Los Alamos National Laboratory*
*Los Alamos, NM 87545, USA*



ABSTRACT

A cylindrical, completely enclosed Rayleigh-Bénard convection cell with radius-to-height ratio $\Gamma=1/2$ is subjected to impulsive spin-up about its vertical axis. Our study produces TLC (thermochromic liquid crystal) temperature measurements and PIV (particle image velocimetry) velocity reconstruction of the transient state between the two regimes of turbulent convection corresponding to the cell at rest and in steady rotation. The most persistent transient feature emerging is a sharply defined ringlike pattern characterized by a decrease in temperature and high azimuthal shear. The latter leads to formation of Kelvin-Helmholz vortices. Initially azimuthally regular, the pattern of these vortices loses its regularity and thus completes the transition to rotating convection state.

## 1. Introduction

Problems related to rotating Rayleigh-Bénard convection are relevant for many astronomical, geophysical and engineering applications. Rayleigh-Bénard convection also provides a useful framework for theoretical, experimental and numerical studies of turbulent boundary layers[1]. The present experimental investigation concentrates on the flow structure in a Rayleigh-Bénard cell subjected to impulsive spin-up about its vertical axis. The initial state of the cell is that of turbulent convection in a non-rotating reference frame and the final state is that of rotating turbulent convection. In many cases, the transition between the two produces azimuthally-regular patterns. Before we proceed with the description of our experiment and the results of the observations, we need to define the physical processes relevant for the problem and the corresponding dimensionless parameters.

Rayleigh-Bénard convection occurs in a fluid layer of depth $d$ bounded by a cool rigid surface on the top and a warm rigid surface on the bottom. If the temperature difference between the top and the bottom $\Delta T$ does not exceed a certain critical value, heat is transported through the layer by diffusion alone and the fluid is at rest. For higher temperature differences, the fluid does not remain at rest and heat is transported by a combination of diffusion and advection. There are three governing dimensionless parameters asscociated with the problem. The Rayleigh number which represents the amount of potential energy in the system is $R=\alpha g \Delta T d^3/\nu\kappa$, where $\alpha$ is the coefficient of thermal expansion, $g$ is the acceleration of gravity, $\nu$ is the kinematic viscosity of the fluid and $\kappa$ is the thermal diffusivity. The Prandtl number $\sigma=\nu/\kappa$ is determined by the properties of the fluid. Finally, the geometrical aspect ratio between the characteristic vertical scale $d$ and horizontal scale $r_0$ is $\Gamma=r_0/d$. For sufficiently high Rayleigh numbers, convective flow is dominated by thermal plumes[1].

The presence of rotation adds the Coriolis and centrifugal forces into the problem. The dimensionless parameter proportional to the strength of the Coriolis force is the dimensionless rotation rate $\Omega=\Omega_D d^2/\nu$, where $\Omega_D$ is the angular rotation rate about the vertical axis. Centrifugal effects can be ignored if the centrifugal acceleration is small compared to gravity, as it is in the present study ($\Omega^2 r_0/g<0.1$). An excellent overview of the studies of rotating convection is provided by Boubnov and Golitsyn[2]. In the vicinity of the top surface, features most prominent in the flow are vortices with downwelling (cyclonic) and upwelling (anticyclonic) cores.

If the cell is subjected to impulsive spin-up, the flow is driven by boundary layers that form on the top and bottom surfaces, which draw fluid from the depth of the cell towards the boundaries near the axis and pump it away from the horizontal surface in the regions adjacent to the vertical walls. For spin-up of a free-surface convection cell, Boubnov and Golitsyn[3] report formation of transient azimuthally regular structures. Savas[4] observed azimuthally-regular waves propagating through the top boundary layer in a completely enclosed cell without convection. Will regular structures form in a Rayleigh-Bénard cell upon spin-up? Can the transient flow patterns be mapped to regions in $R$-$\Omega$ parameter space? The present study addresses these questions. The following sections contain the description of the experiment and the outline of our findings.

## 2. Experimental Apparatus and Data Acquisition System

A simplified schematic of our experimental setup is presented in Fig. 1. A cylindrical convection cell with the radius $r_0$=6.35 cm and aspect ratio $\Gamma$=1/2 is positioned on a rotating table. The aluminum bottom plate of the cell is connected to a heating element. The top plate of the cell is a thin (3.2 mm thick) sapphire window separating the cell from a cooling manifold. Temperature-controlled water circulates through the manifold ensuring uniform constant temperature of the top surface, while heat is applied at the bottom surface. Horizontal sections of the flow are illuminated by a sheet of white light 2 to 4 mm thick. A color digital video camera records 30 views of the illuminated section of the cell per second with a resolution of 640 by 480 pixels. With the cell filled with water which is seeded with neutrally buoyant polystyrene microspheres, the particle image velocimetry (PIV) technique is applied to the digital video recordings to reconstruct the field of horizontal velocity components in the plane of the light sheet. For an overview of the PIV technique and its applications refer to Adrian[5]. Instead of polystyrene microspheres, the flow can be seeded with capsules containing thermochromic liquid crystals (TLC) that change the color of the light they scatter with temperature.

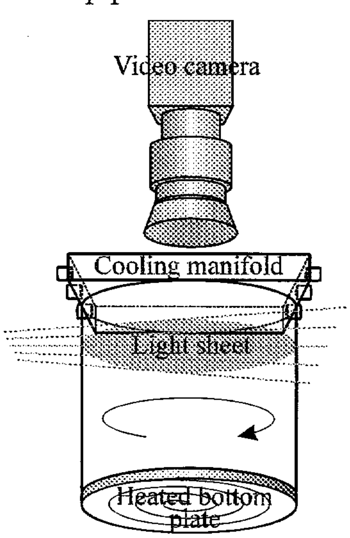

Fig.1. Schematic of experimental setup

Thus a temperature field in the illuminated section of the cell is acquired. A detailed description of the setup and data acquisition techniques used in the experiments, as well as the study of the accuracy of the measurements, are presented elsewhere[6].

### 3. Observations

We investigate region of parameter space $5\times10^7<R<5\times10^8$ and $0<\Omega<8\times10^4$. Within a large part of this region, regular structures form during spin-up. Fig. 2 shows the possible flow patterns and transitions between them for a fixed $R=2\times10^8$ in terms of temperature maps acquired near the top of the cell. Bright and dark areas in the maps represent hot (upwelling) and cold (downwelling) flow correspondingly. Time is nondimensionalized by the Ekman spin-up time $\tau_E=d(\nu\Omega_D)^{-1/2}$, which is the characteristic time scale for impulsive spin-up of the cell without convection.

The features of the initial condition (no rotation, Fig. 2, upper row) are irregular upwelling plumes separated by elongated zones of downwelling flow. Appearance of the final condition of the flow in steady rotation (Fig. 2, bottom of each column) depends on the rotation rate. For slower rotation ($\Omega=4\times10^3$, Fig. 2, first column), lines of downwelling flow are still present, although one can also observe vortices. At higher rotation rates, the only structures in the flow are vortices. The number of vortices per unit area increases with the rotation rate, consistent with the observations of Boubnov and Golitsyn[3]. The steady states of rotating convection can also be characterized in terms of Rossby number, $\mathrm{Ro}=(2\Omega)^{-1}R^{1/2}\sigma^{-1/2}$. Julien *et al.*[7] suggested that Ro=1 defines the separation between weakly and strongly rotating flows. Heat transport measurements by Liu and Ecke[8] and the present work support this separation criterion. For $\Omega=4\times10^3$ and $R=2\times10^8$, Ro is close to unity and there are plumes and cold lines in the flow field along with vortices, whereas for the higher rotation rates shown the Rossby number is less than one and the flow is clearly vortex-dominated.

The pattern of transition between the initial and final states depends on the rotation rate. Spin-up to low rotation rates ($\Omega<6.4\times10^3$ for $R=2\times10^8$) produces no azimuthally regular patterns. The lines of downwelling flow present in the initial conditions are warped by spin-up but never completely suppressed, and some vortices form (Fig. 2, left column). As the final rotation rate increases past $\Omega\sim6.4\times10^3$, however, a more complex pattern of flow evolution emerges. The spin-up is strong enough to destroy the memory of the initial conditions for $\Omega>6.4\times10^3$, producing a uniform temperature field near the top shortly upon spin-up (Fig. 2, second image, second row). One then can observe cool fluid being swept towards the vertical boundaries of the cell. At the next stage, one or more cold rings form, with the condition $\Omega<4.5\times10^4$ separating the one-ring case from the multiple-ring cases at higher rotation rates. The radii of the rings show only weak dependence on $R$ and $\Omega$, with the first (inner) ring forming at $r\approx3/4\ r_0$ and the second (outer) ring forming at $r\approx0.95\ r_0$. Eventually vortices roll up in the ring(s) and destroy them (Fig. 2, fourth row). For $\Omega\geq7.2\times10^4$, prior to the roll-up of the vortices in the outer two rings, an innermost third ring forms at $r\approx0.52\ r_0$ and is likewise destroyed by roll-up of vortices. In the case of more than one ring, the vortices form a staggered structure. After the vortices emerge, the flow loses azimuthal regularity, and the transition to steady state rotation is completed.

We observed similar bifurcations of the flow pattern with change in $\Omega$ for higher and lower Rayleigh numbers[6]. It is interesting that $\Omega$ corresponding to each transition boundary (from no rings to one ring, etc.) increases with increasing $R$, likely because stronger turbulent convection at higher R requires stronger radial shear flow, i.e. higher final rotation rate, to maintain azimuthal regularity and suppress instabilities. Table 1 contains the values of $\Omega$ and $R$ defining the stability boundaries for each flow pattern.

Table 1. Spin-up patterns in $R$-$\Omega$ space

| $R$ | $\Omega$ (no rings) | $\Omega$ (1 ring) | $\Omega$ (2 rings) | $\Omega$ (3 rings) |
|---|---|---|---|---|
| $5\times10^7$ | $0<\Omega<5\times10^3$ | $5\times10^3<\Omega<3.4\times10^4$ | $3.4\times10^4<\Omega<6.9\times10^4$ | – |
| $2\times10^8$ | $0<\Omega<6.4\times10^3$ | $6.4\times10^3<\Omega<4.5\times10^4$ | $4.5\times10^4<\Omega<7.2\times10^4$ | $\Omega>7.2\times10^4$ |
| $5\times10^8$ | $0<\Omega<1.3\times10^4$ | $1.3\times10^4<\Omega<4.7\times10^4$ | $4.7\times10^4<\Omega<7.6\times10^4$ | $\Omega>7.6\times10^4$ |

At the lowest Rayleigh number investigated, $R=5\times10^7$, we did not observe the three-ring pattern, whereas for $\Omega=6.9\times10^4$ and higher rings no longer formed. This may be an artifact of the temperature field acquisition system. The range of color play of the TLC microcapsules we used was 4°C, while the temperature difference $\Delta T$ between the top and the bottom plates was only 0.85°C at the lowest Rayleigh number. With the temperature measurement error on the order of 0.1°C, as estimated in our earlier work[6], the temperature gradients in the ring(s) may have been too small to be resolved.

Additional insight into the structure of the flow during spin-up is provided by velocity field measurements obtained via PIV. The azimuthal velocity $v_\phi$ magnitude map in Fig. 3 ($R=2\times10^8$) shows that the ring is associated with a local minimum in velocity, indicating the presence of downflow and strong shear at the location of the cold ring in temperature maps.

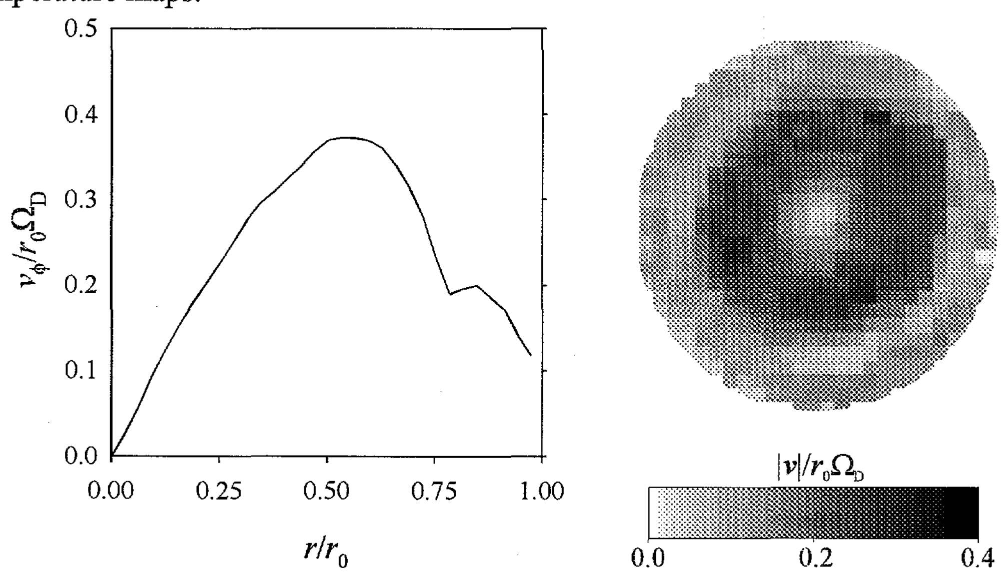


Figure 3. Instantaneous azimuthal velocity profile (left) and velocity magnitude map (right) for spin-up to $\Omega=2\times10^4$, $R=2\times10^8$, dimensionless time $t/\tau_E=0.5$.

This shear leads to roll-up of Kelvin-Helmholz vortices that eventually destroy the ring. Vertical-wall azimuthal velocity upon spin-up $r_0\Omega_D$ was used for nondimensionalization.

## 4. Conclusions

Sequences of instantaneous temperature and velocity maps in the plane adjacent to the top surface of a Rayleigh-Bénard cell provide quantitative information about the flow patterns forming during the impulsive spin-up of the cell about its vertical axis. For a fixed Rayleigh number, the type of the transient flow pattern depends on the final rotation rate of the cell. Spin-up to low rotation rates (Rossby number on the order of 1 or greater) leads to modification of the flow patterns initially present in the cell. If the final rotation rate exceeds a certain critical value dependent on the Rayleigh number, the spin-up is strong enough to obliterate the initial distribution of temperature and velocity and form an azimuthally uniform distribution of temperature and velocity. From this distribution, one, two or three rings of cold downwelling flow evolve. The number of the rings depends on the rotation rate. Rotation rates characterizing the transition between the patterns increase with increasing Rayleigh number. The rings are characterized by a drop in temperature and azimuthal velocity. Shear in the rings leads to Kelvin-Helmholz instability, resulting in roll-up of vortices and destruction of the rings. The formation of vortices leads to loss of azimuthal regularity and emergence of the vortex-dominated flow pattern characteristic of strong rotating turbulence.

## 5. Acknowledgements

We gratefully acknowledge Ömer Savas for providing his PIV code for the analysis of the data presented in this paper. This research was funded by the U.S. Department of Energy.

## 6. References

1. E.D. Siggia, Annu. Rev. Fluid Mech. 26 (1994), 137.
2. B.M. Boubnov and G.S. Golitsyn, Convection in rotating fluids (Dordrecht; Boston, Kluwer Academic, 1995).
3. B.M. Boubnov and G.S. Golitsyn, J. Fluid Mech. 23 (1986), 503.
4. Ö. Savas, Phys. Fluids 26 (1983), 3445.
5. R.J. Adrian, Annu. Rev. Fluid Mech. 23 (1991), 261.
6. P. Vorobieff and R.E. Ecke, submitted to Phys. Fliuds (July 1997).
7. K. Julien, S. Legg, J. McWilliams, and J. Werne, J. Fluid Mech. 322 (1996), 243.
8. Y.M. Liu and R.E. Ecke, preprint.