DRIFTING CONVECTION ROLLS INDUCED BY SPATIAL MODULATION

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ABSTRACT

A sinusoidal variation of the height of a convection channel gives rise to the onset of time dependent convection. The drift rate of the convection rolls is proportional to the amplitude of the modulation, to the sine of the phase difference between the modulation at the upper and lower boundary and to the amount of asymmetric properties of the convecting fluid such as the curvature in the temperature dependence of the density. These results have been obtained experimentally through the measurement of convection in an annular channel heated from below.

INTRODUCTION

Rayleigh-Bénard convection is usually studied in the case of horizontally uniform external conditions. For many applications in geophysics or in engineering problems inhomogeneous conditions in the horizontal dimensions are encountered, however, and the role played by spatial modulations of external parameters becomes an important question. The problem of sinusoidal modulations of the height of the convection layer or of the temperatures at the boundaries was considered by Kelly and Pal (1978) and Pal and Kelly (1978). In this paper we report experimental observations of the onset of convection in a channel heated from below with a sinusoidally varying height.

Since the local Rayleigh number varies in a spatially modulated system, the onset of convection occurs inhomogeneously. Because of the spatial order imposed by the local variations of the Rayleigh number one might expect even less variations in time of the convection flow than in the case of a homogeneous layer. Indeed, the analysis of Kelly and Pal predicts a stationary onset of convection even in cases when the sinusoidal modulations at the lower and upper boundaries are out of phase. The experimental observations described in the following demonstrate the unexpected phenomenon of time dependent convection near threshold. A detailed analysis of the problem to be published elsewhere traces the origin of the discrepancy between existing theory and laboratory measurements to the neglection of non-Boussinesq effects by Kelly and Pal (1978).

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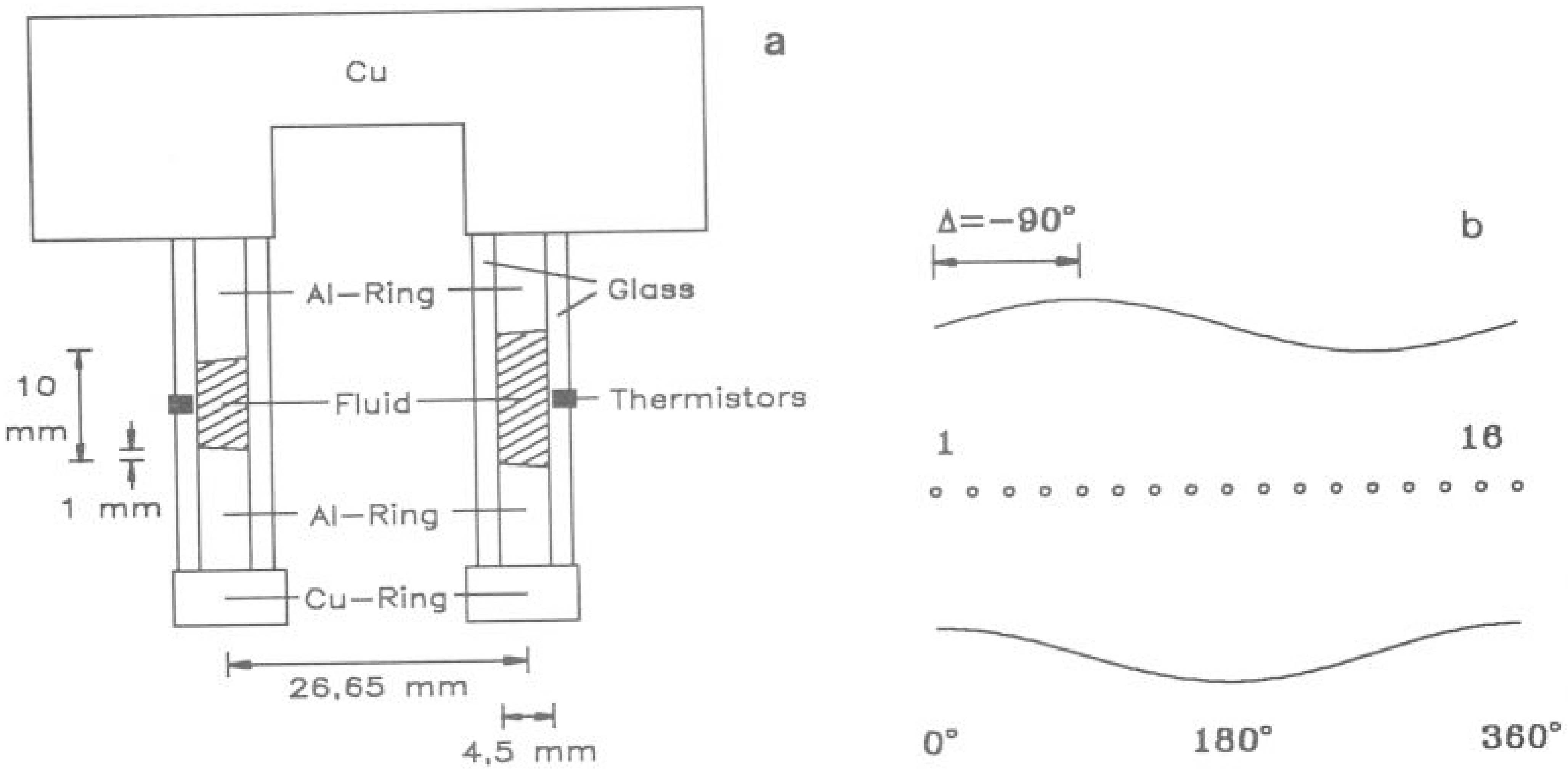

Fig. 1. a) Cross section of the convection apparatus. Domain of convecting fluid is hatched.

b) Postition of the thermistors and definition of the phase shift angle Δ.

THE ANNULAR CONVECTION CHANNEL

A cross-section of the cell used in the experiments is shown in figure 1a. In order to achieve periodic boundary conditions in one of the horizontal dimensions the cell was constructed as an annulus. Two anodized aluminium rings form the upper and lower boundaries. The inner and outer cylindrical boundaries are made out of plexiglas®. The upper copper block is kept at a constant temperature by a thermostatically controlled water bath, while the temperature difference is produced by a current flowing through a constantan wire which is winded around the lower copper ring. Copper constantan thermoelements are used to measure the temperature difference. The dimensions of the fluid container are also shown in figure 1a. The mean height, thickness and diameter of the annular fluid channel are 10, 4.5 and 25.65 mm, respectively. The variation of the upper and lower boundary with an amplitude of 1 mm was produced by oblique cuts of the aluminum rings which yield a sinusoidal variation of height along the circumference. Since the phase of modulation at the upper and lower boundaries is arbitrary, a general variation of height as shown in figure 1b is obtained. 16 thermistors are placed equidistantly in the outer plexiglas ring at the equatorial plane of the annular channel cell. Thermistor 1 is placed above the maximum height of the lower boundary and defines the origin of the coordinate around the circumference.

EXPERIMENTAL OBSERVATIONS

In order to realize a convecting fluid with asymmetric material properties, the annular channel was filled with water at a mean temperature near 4° C. The onset of convection is demonstrated in figure 2. To obtain optimal sensitivity for the onset of convection the thermistor signal at a temperature difference below the critical value has been subtracted from the measured signal. For better presentation of the data, the data for the interval $0° < \varphi < 180°$ are repeated for $360° < \varphi < 540°$.

The lines through the data are obtained by a Fourier series interpolation. In figures 3 and 4 only these interpolating functions are shown for simplicity . As must be expected the onset of convection occurs first at φ=135° where the maximum height of the channel is located. With increasing ΔT the entire channel is filled with convection rolls.

In order to visualize the time dependence of convection the thermistor signals must be recorded at different times for a fixed value of ΔT. Figure 3 shows typical results for opposite values of the phase shifts, Δ=-90° and Δ=+90°. At the onset of convection the rolls drift in the direction in which the channel is bent upwards (see figure 1b). Once the entire channel is occupied by convectiton rolls the drift is reversed. In both cases the average drift is roughly proportional to sinΔ. At Δ=180° the opposite drift is observed on the two sides of the maximal height. Occasionally a drift is observed even at Δ=0° due to imperfections of the channel. Because of the two different mechanisms for the drift apparent in the data it is not surprising that steady convection rolls are sometimes observed in parts of the channel as shown in figure 4. It has also been found that states with different numbers of rolls can be realized and that elimination of a roll pair can give rise to hysteresis phenomena when the Rayleigh number is increased first and decreased subsequently.

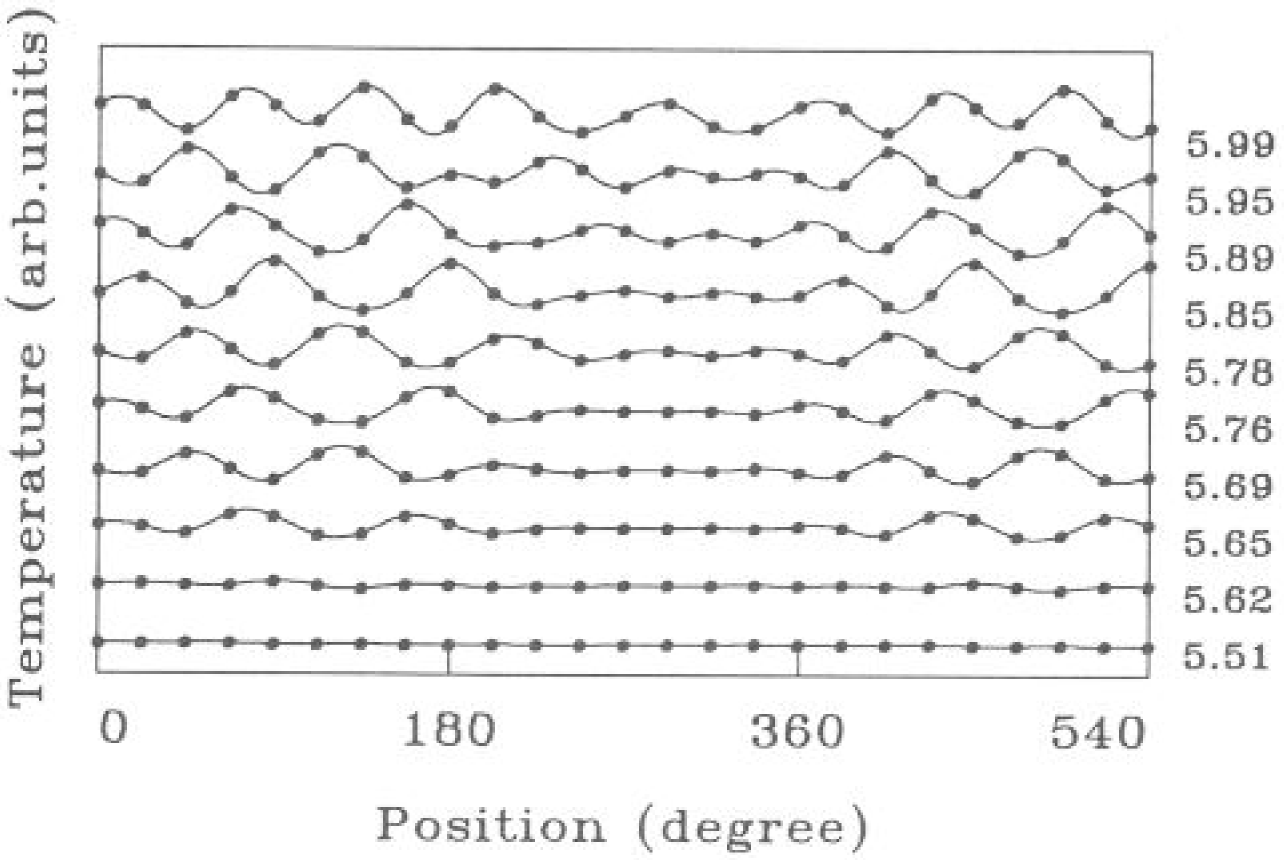

Fig. 2. Onset of convection for Δ=-90°. The numbers at the right side are the applied temperature differences. The mean temperature varies between 3.6° C and 3.8°C. The abscissa gives the angle φ measured in degrees.

DISCUSSION

In the presence of a modulation the basic state before onset of convection is characterized by a circulation with the spatial periodicity of the modulation. The advection by this circulation of the packets of the convection rolls appearing at the onset of convection seems to be responsible for the time dependence shown in figure 3a,c. As the convection becomes distributed more uniformly throughout the channel, the effects of the advection by the basic circulation cells tend to cancel in

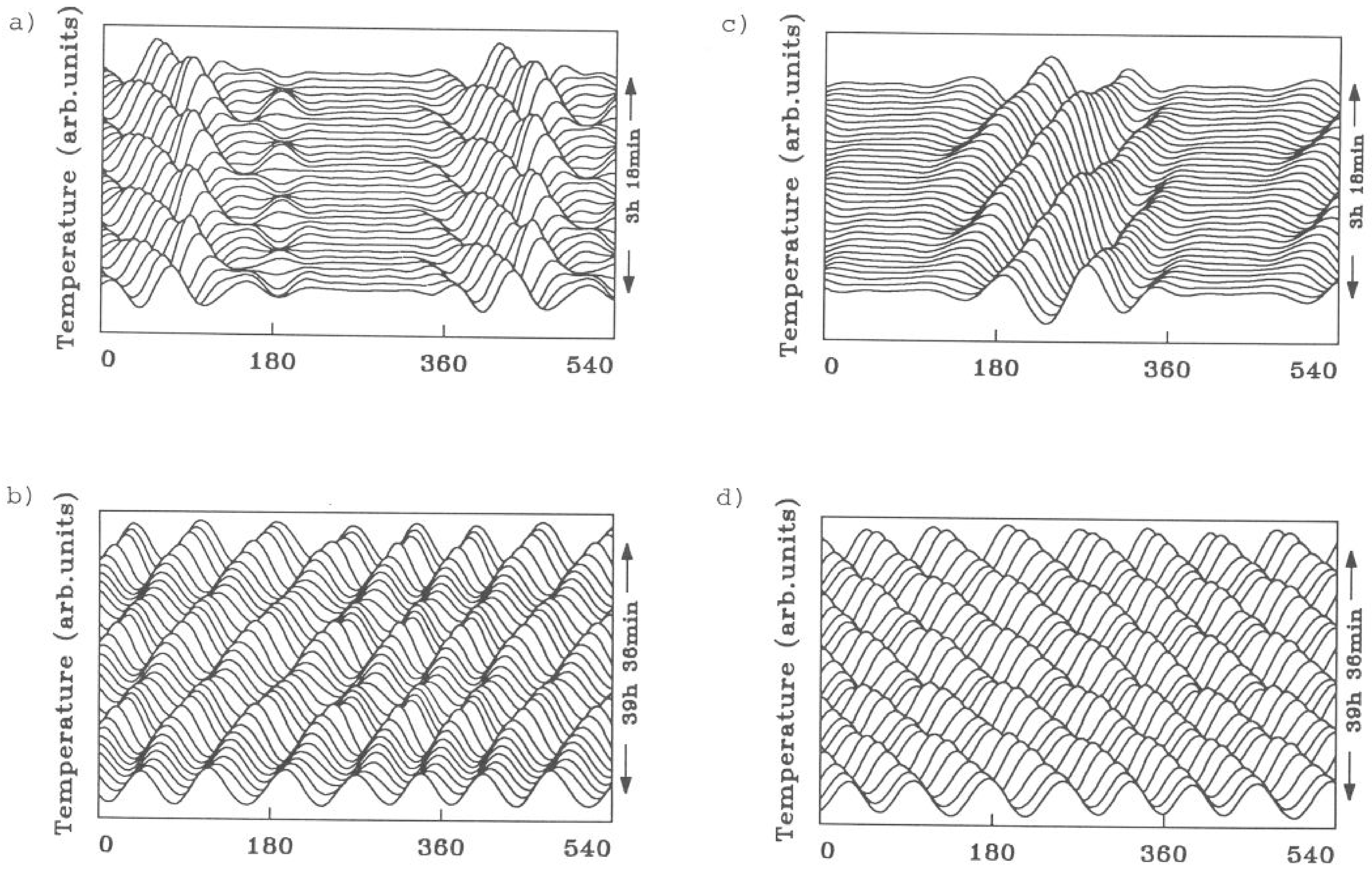

Fig. 3. Time dependence of convection. The lines represent measurements at equidistant time interval. The entire duration of the measurements is indicated on the right side of each graph.

a) $R = 1.02\ R_c$, $\Delta = -90°$, $T_{mean} = 3.7°$

b) $R = 1.21\ R_c$, $\Delta = -90°$, $T_{mean} = 4.3°$

c) $R = 1.01\ R_c$, $\Delta = +90°$, $T_{mean} = 4.3°$

d) $R = 1.26\ R_c$, $\Delta = +90°$, $T_{mean} = 4.9°$

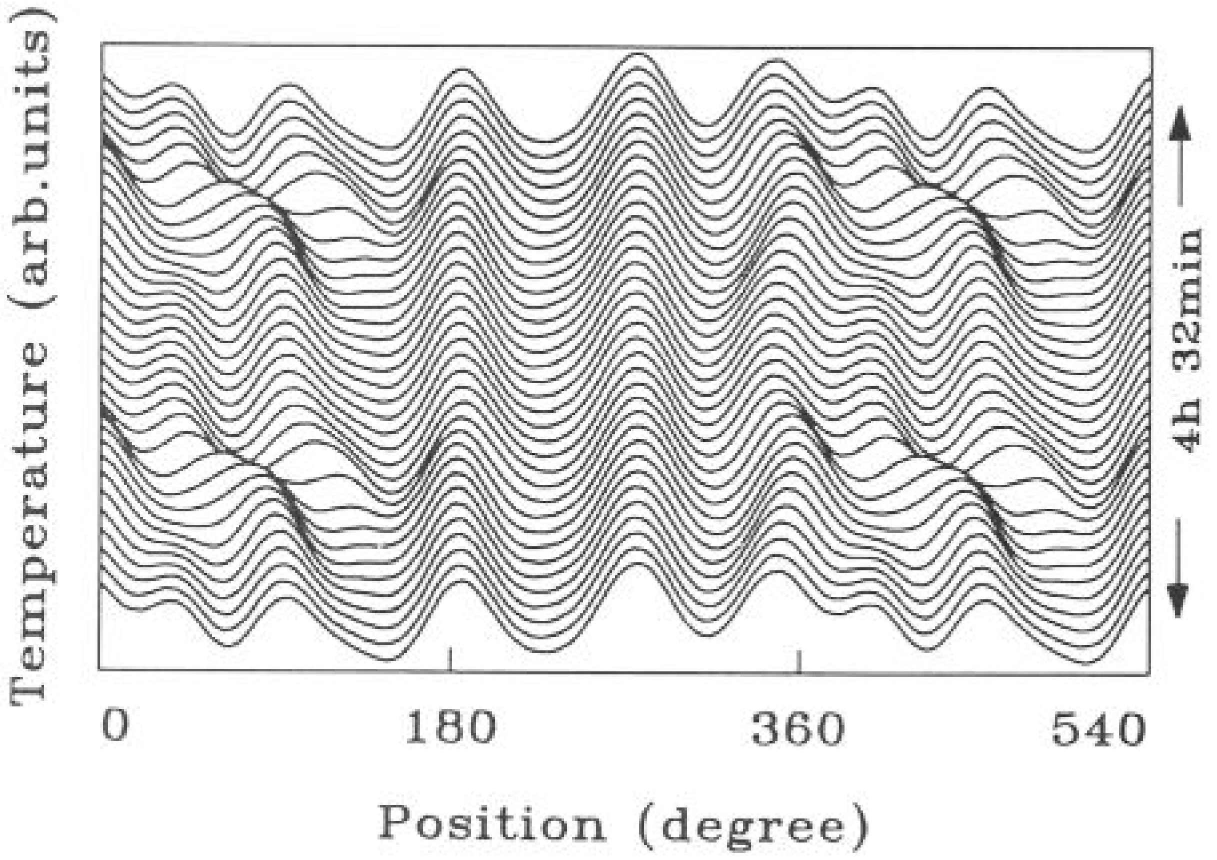

Fig. 4. Convection in the channel for R = 1.09 R_c, Δ = +90°, T_{mean} = 4.5° at equidistant times. This figure indicates the coextistence of steady and drifting convection roles.

different regions of the channel. On the other hand a weaker nonlinear influence of the basic circulation cells becomes noticeable. Through Reynolds stresses a mean azimuthal flow is generated in the channel which causes the advection of the convection rolls in the opposite direction. Both types of advection depend on the asymmetry of the fluid channel in the vertical direction. Without this asymmetry the effects of advection vanish in agreement with the theoretical model of Pal and Kelly (1978).

It is not appropriate to outline the theory of the phenomena in more detail at this time, since not all numerical computations have yet been completed. Characterizing the amplitude of modulation by δ and the amount of asymmetry by γ we find that the drift near onset is of the order $\gamma\delta\sin\Delta$ while at higher Rayleigh number a drift of the order $\gamma\delta^2\sin\Delta$ is found. A detailed comparison between theoretical predictions and experimental measurements will be given in a future paper.

ACKNOWLEDGEMENT

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