Periodic convection in liquid ^{4}He close to onset

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Abstract

High resolution images of convective flow patterns in a vertical axis cylindrical layer of normal fluid helium of diameter 18.25 mm and height 0.56 mm have been obtained near the Prandtl number minumum of 0.5 at 2.6 K. The primary stationary pattern close to the convection threshold is a robust state of straight parallel rolls signalling that the boundary conditions are close to ideal. A periodic response exists at slightly higher Rayleigh numbers in which dislocations climb periodically along the roll axes through the skew-varicose mechanism. Correlated with this regime are periodic oscillations of amplitude 100 μK and period of the same order as the horizontal thermal diffusion time. The dynamics of the periodically varying pattern and of more chaotic patterns at higher Rayleigh numbers are revealed using time-lapse movie sequences of the images.

Key words: helium4, instability, convection, pattern

1. Introduction

Convection in a thin horizontal fluid layer heated from below (Rayleigh – Bénard convection) has long been used to study nonlinear phenomena and the physics of pattern formation. The control parameter in convection is the Rayleigh number R, a dimensionless form of the temperature difference across the fluid layer. Below a critical value of the Rayleigh number, R_c, only conduction transfers heat across the fluid layer; above R_c the heat transport due to conduction is augmented by convection. We study convection in ^{4}He in a cylindrical cell of height 0.56 mm and diameter 18.25 mm (aspect ratio = radius / height = 16.3) at a temperature of 2.617 K where the Prandtl number is 0.50. The Prandtl number is the ratio of the kinematic viscosity to the thermal diffusivity of the fluid, and is a minimum at this temperature.

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2. Previous Work

Gao and Behringer [1], using ^{4}He as their fluid (Prandtl number 0.54 – 0.70) in a cylindrical cell, observed a periodic modulation of the temperature difference across the fluid layer when R exceeded 1.09 R_c. The amplitude and frequency of this modulation increased with increasing R. Later experiments by Behringer et al [2] also demostrated the existence of a periodic regime in a cell of rectangular geometry (Prandtl numbers 0.52 and 0.70). At the time of these experiments, there was no method of directly probing the fluid layer to gain information about the flow pattern. Despite this, the skew-varicose instability [1,3] was suggested as a possible mechanism for generating these oscillations.

Previous experiments by us [4] combined thermal measurement techniques and the optical shadowgraph technique [5] to directly probe the flow dynamics of the fluid layer. Matley et al [4] observed the initial flow state above onset of convection to be an imperfect concentric ring pattern caused by non-uniformities in the boundary conditions. A modulation of the temperature difference was observed in the regime $1.06 < R < 1.15$

and was correlated with a repeating pattern revealed by the shadowgraph images.

3. Recent Results

The current experimental cell has been modified to eliminate major imperfections in the physical and thermal boundary conditions. The initial flow state above the onset of convection is now observed to be a straight parallel roll pattern: this is due to the improvements in the thermal boundary conditions of the sidewalls.

We again observed a modulation of the temperature difference: with the modified cell this occurred when $R > 1.13R_c$. Figure 1 shows this modulation as a percentage of the critical Rayleigh number R_c for a mean Rayleigh number of $1.33R_c$. The period of this modulation is of the same order as the horizontal thermal diffusion time which is the time required for the fluid in the centre of the cell to experience the effects of the sidewalls. In our experiment the horizontal thermal diffusion time is approximately half an hour. This thermal data was correlated with a periodic deformation of the straight roll pattern. The straight roll pattern is perturbed by a local shear in the flow caused by the skew-varicose instability [3]. This creates a disclination [6] that squeezes two sets of rolls together. The two sets of joined rolls move across and along the roll axis away from the disclination point towards the sidewalls where they are absorbed. Figure 2A shows the convection pattern formed at the onset of convection, a straight roll time-independent pattern. Figure 2B shows the pattern during a periodic deformation, the two sets of joined rolls starting to move away from the disclination point towards the sidewalls.

As in our earlier work [4], as R is increased, periodicity gives way to an aperiodic regime in which spatio-temporal chaotic patterns exhibiting spirals are observed. A possible interpretation of this regime is that it is an extension to small aspect ratios of the spiral defect chaos state observed in compressed gases [8].

4. Conclusion

In this paper we have provided compelling evidence that the modulation of the temperature difference seen by us and others is caused by the skew-varicose instability. It appears from reviews [7] of existing literature that this flow regime is found only in liquid ^{4}He; further work is needed in fluids of comparable Prandtl number to ascertain if ^{4}He is unique in this regard.

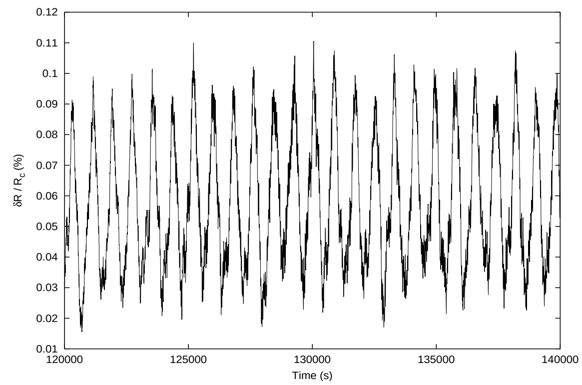

Fig. 1. Modulation of the Rayleigh number normalised by the critical Rayleigh number R_c. Mean value of Rayleigh number $R = 1.33R_c$.

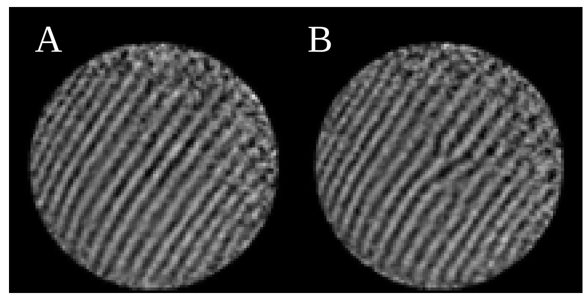

Fig. 2. A. Straight roll pattern seen just above onset of convection. B. Straight roll pattern undergoes deformation due to skew-varicose instability.

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