Forced Phase Diffusion in a Convection Experiment

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In a thermal-convection box the boundaries parallel to the convection rolls are replaced by ramps, i.e., smooth variations in the Rayleigh number from supercritical to subcritical values. Such a geometry selects a small wavelength band. The wavelengths selected by the left and right ramps are not necessarily the same — resulting in a wavelength gradient. This gradient leads to forced phase diffusion: The convection pattern drifts from the short-wavelength end to the ramp selecting the longer wavelength. An experimental observation of this phenomenon is presented.

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Homogeneous systems driven from equilibrium can develop a spatial structure when a threshold value of an external forcing parameter is exceeded. The most popular examples in fluid dynamics are Rayleigh-Bénard convection and Taylor-Couette flow. A general problem for these systems is wavelength selection: At the threshold value the wavelength is well defined, but above this critical point a band of stable wavelengths opens up. The question arises whether there is any wavelength within this band which is preferred.

Experiments with normal boundaries give no hint for such a preferred wavelength. All wave numbers within the Eckhaus band are stable, and the wavelength is selected by the fact that an integer number of rolls has to fit into the box. In order to overcome this restriction one is led to the idea of a ramp: The order parameter is changed slowly and smoothly in space from supercritical to subcritical values. Such a ramp does indeed select a single wavelength.[1,2] It has been shown theoretically,[1] however, that this selected wavelength is not unique. In the case of Rayleigh-Bénard convection the selected wavelength has been calculated as a function of the geometrical and thermal properties of the ramp.[3] It was also shown by a general argument that any wavelength within the Eckhaus band can be reached by means of a suitable ramp.[3] This nonuniqueness leads to an interesting effect: If the two ramps in a convection channel disagree on the wavelength to be selected, a wavelength gradient is established in the bulk (nonramped) part of the system. This is an unstable situation leading to phase diffusion: The convection pattern drifts through the channel from the short-wavelength end towards the ramp selecting the longer wavelength. In this Letter the experimental observation of this phenomenon in a ramped convection channel is presented.

The convection channel is cut out of a copper plate (see Fig. 1). The bulk part of the channel is 3 mm high, 1.5 mm thick, and 18 mm long. The ramps adjacent to this central part decrease the height of the channel from 3 to 1 mm over a length of 26 mm by means of a parabolic curvature of the top and bottom. For some of our experiments one of these ramps has been replaced by a ramp with a pinning center[2,4,5] as indicated by the dashed line in Fig. 1. The experiment takes place in an aluminum box regulated to $20 \pm 0.02\,^\circ\mathrm{C}$ forming a thermal and electrical shield. The top of the convection channel is attached to this isothermal box. The bottom is heated with an electrical heater with a voltage stability of better than 0.01% and is thermally isolated by a Styrofoam mantle. The temperature difference between top and bottom is measured with a pair of thermocouples and has a stability of better than 0.3%. Additional side heaters are placed above the ramps in order to influence their thermal properties. To decrease the temperature gradient across the bulk part of the channel, slits of 1 mm thickness are cut into the copper plate. Glass plates of 1 mm thickness are attached to the sides of the copper plate in order to allow flow visualization from the side. Purified cyclohexane is used as the working fluid.

The shadowgraph technique is used to visualize the flow field from the side: Parallel light is deflected by the density gradients of the fluid caused by the convection.

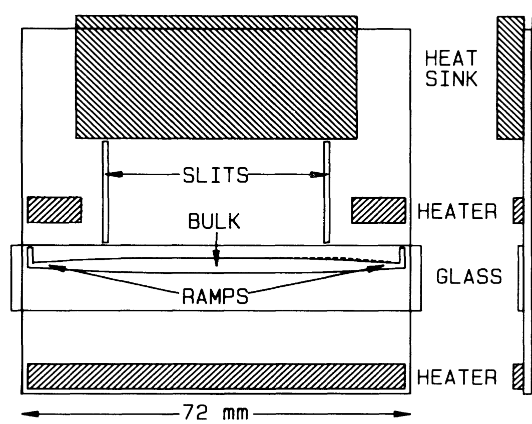

FIG. 1. The convection channel is cut out of a copper plate of $72\times72\times1.5$ mm^3. The dashed line indicates the pinning center.

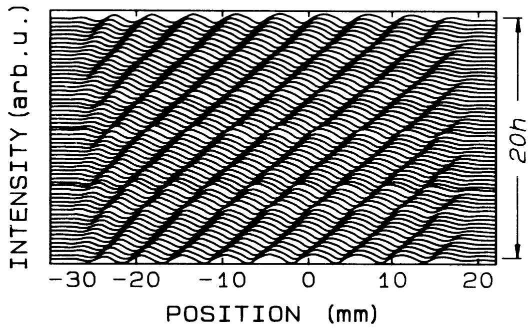

FIG. 2. Drifting convection patterns measured by the shadowgraph method at $\epsilon=0.72$. The image intensity is shown as a function of position along the long dimension of the channel. The position 0 mm corresponds to the middle of the channel.

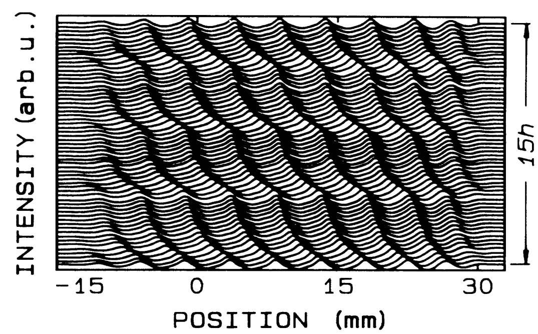

FIG. 3. Drifting convection pattern influenced by a pinning center at $\epsilon=0.50$. Now the phase of the velocity field with respect to the location of the pinning center influences the pattern, thus giving rise to the observed nonuniform drift velocity.

A photodiode, movable parallel to the long dimension of the channel by means of a stepping motor under computer control, is used to scan the light intensity at a distance of typically 50 cm behind the channel. At first such a horizontal line scan is taken in the absence of convection. Further line scans are then divided by this zero image in order to remove the spatial inhomogeneities of the measured light intensity. This method is convenient for the measuring of the critical point for the onset of convection. The critical temperature difference of 2.63 K measured for our channel is well within the range given by the theoretical predictions for perfectly insulating and perfectly conducting sidewalls.[6]

Figure 2 demonstrates the existence of a drifting convection pattern in the channel without the pinning center. Line scans of the light intensity along the channel are shown. At time intervals of 20 min, 61 scans are taken, thus spanning a time period of 20 h. They are plotted on top of each other in the figure. The spatial light modulation is caused by the convection pattern: Colder regions (sinking fluid) cause high-intensity peaks, warmer regions (rising fluid) decrease the intensity. Figure 2 thus indicates that the convection rolls are generated in the left ramp, drift throughout the channel (position 0 indicates the middle of the channel) and decay on the right-hand side. Note that the rolls become visible at a position close to -30 mm, but decay already at a position of $+20$ mm. This difference in the position of the critical points is caused by the extra heater located on top of the right-hand ramp.

In order to increase the difference between the critical Rayleigh numbers R_c and R_d for the onset of convection and the onset of the drift, respectively, a pinning center[4,5] (see Fig. 1) similar to the one used in Taylor-Couette flow experiments[2] was added to the channel. Figure 3 shows the movement of the pattern obtained in this case: It is less uniform as compared to Fig. 2. Note that the heater at the left-hand side is used here.

Figure 4 gives information about the drift velocity as a function of the reduced Rayleigh number $\epsilon=(R-R_c)/R_c$ for the channel with the pinning center. A photodiode, located at a fixed position, measures a periodic time signal caused by the periodic convection pattern passing by. We determine the frequency of this periodic signal by means of a fitting procedure. This frequency is plotted in Fig. 4.

As indicated in Fig. 3, the velocity within one period of the movement is not constant. In order to measure this velocity we take the intensity data out of the range from -9 to $+9$ mm (the bulk part of the channel). The distance traveled within 20 min is obtained by means of the spatial cross-correlation function between two consecutive lines. In addition the wavelength gradient of the convection rolls can be extracted from the line scans. For this purpose we measure the distance between two intensity maxima, which gives the wavelength. Within the range of ± 9 mm at least three maxima can be measured, and a wavelength gradient can thus be determined. Figure 5 shows these two measurements for a point slightly above R_d ($\epsilon=0.42$, $f=0.05$ mHz) in Fig. 4. The positive sign of the gradient indicates that the

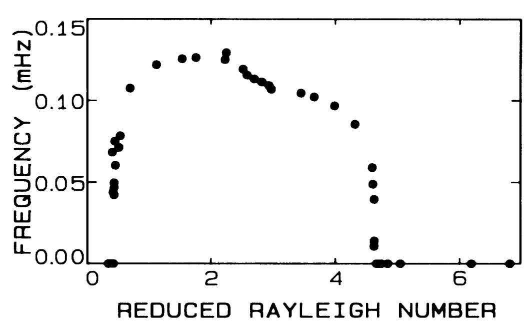

FIG. 4. The frequency of the time-periodic intensity modulations observed by a photodiode located at a fixed position as a function of $\epsilon=(R-R_c)/R_c$. This frequency is proportional to the drift velocity of the pattern. A frequency of zero indicates that within 24 hours of waiting time no hint of a movement of the pattern was observed.

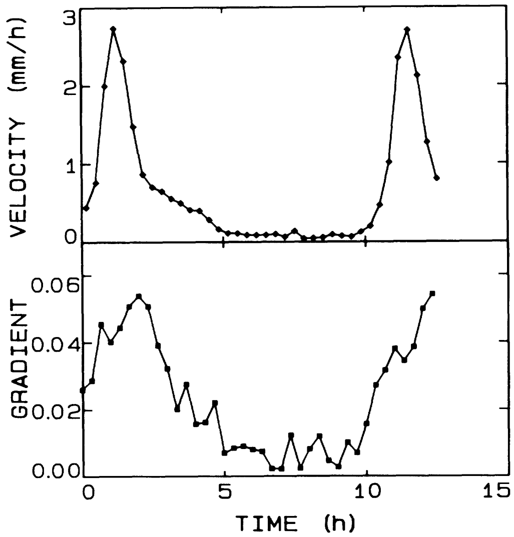

FIG. 5. The spatial wavelength gradient and the drift velocity of the convection pattern within one period for $\epsilon=0.42$.

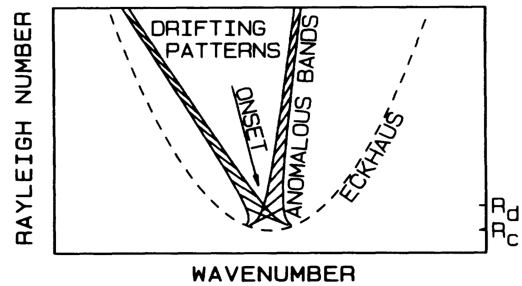

FIG. 6. Schematic explanation for the observed phenomena. The two shaded regions indicate the wave numbers selected by the two ramps. These bands open up close to R_c, and therefore they overlap in a finite region above R_c. Drift sets in at the critical point R_d, where the overlap ceases. The wave-number gradient and therefore the velocity approach zero at R_d.

wavelength is shorter at the right-hand side, i.e., the pattern drifts from the short-wavelength end to the ramp selecting the longer wavelength. A striking feature is the strong variation of the velocity as a function of the drift phase close to the critical point R_d for the onset of the drift.

Figure 6 presents the qualitative explanation for the experiment. Two different ramps may lead to two different selection bands as indicated by the two shaded regions. In an experimental situation with ramps of a finite length, these bands are not infinitely small as in the case of perfect selection. They rather have a finite width, opening up in the neighborhood of the critical point (anomalous bands).[4,5] Because of this finite width the selection bands overlap within the range $R_c < R < R_d$, and no drift of the pattern occurs. At the critical point R_d the overlap ceases. The different wavelengths selected by the two ramps give rise to a wavelength gradient and thus to drifting patterns, with a drift velocity proportional to that gradient. Note that the gradient is increasing linearly from zero in the neighborhood of R_d, in agreement with the data presented in Fig. 4. A similar picture can be drawn for the upper range of the drift in the neighborhood of $\epsilon=5$. Here the subcritical part of the ramp decreases in size with increasing ϵ and finally vanishes with the result that the width of the anomalous bands increases.[3] As the two bands overlap again, the drift stops.

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