1. Overview

This project focused on understanding the dynamics of a well-controlled fluid system driven far from equilibrium. The goal of the work was to gain a quantitative understanding of the role that traveling waves play in determining patterns and dynamics in such systems. Convection was studied in a horizontal layer of a binary fluid mixture of ethanol and water confined in a variety of interesting geometries, including a narrow annulus, to study one dimensional phenomena, and a large aspect ratio container to study two-dimensional phenomena. In these mixtures, the Soret effect couples the temperature and concentration fields leading to a wide range of dynamical behavior not present in convection in pure fluids. In particular, over a wide range of parameters, when the fluid is heated from below, convection takes the form of traveling waves composed of locally parallel rolls that move perpendicular to the roll axes. The system thus provides an insightful model for studying traveling-wave phenomena in systems driven far from equilibrium. Over the course of the project, a number of important questions were addressed. To a lesser extent, variants of this situation were also studied, including the patterns and dynamics when the fluid is heated from above. At the end of the grant, work focused on so-called non-Boussinesq effects, where there the fluid parameters vary with height in the convection cell, beyond that which can be taken into account by a thermal expansion coefficient.

2. Technical approach

Beyond the conventional techniques to study convection in a thin horizontal fluid layer with good temperature control of the upper and lower boundaries, techniques were developed to study very large convection cells. As a result, patterns of large lateral extent, D, could be investigated (i.e., $D \geq 40d$, where $d$ is the height of the fluid layer, and the pattern wavelength, $\lambda = 2d$). Experimental capabilities were developed to achieve good temperature uniformity over annular, circular, rectangular and oval convection cells as large as 21 cm in lateral extent. The entire pattern could be visualized from above using the shadowgraph technique. A shadowgraph was developed that is capable of imaging the entire pattern with excellent sensitivity and uniformity, free from distortions, over the entire the entire pattern.

3. Key results
3.1 Traveling wave phenomena

- Transition from Traveling-Wave to Stationary Convection in Fluid Mixtures. This study examined in detail the nature of the transition to stationary convection that occurs when the temperature difference across the fluid layer is increased [1]. It is a forward bifurcation with the phase velocity of the waves going continuously to zero.

- Confined States of Traveling-Wave Convection. In this physical system there is a remarkable phenomenon in one-dimensional geometries, in which finite amplitude convection can coexist stably with regions of zero flow. The nature of these states was studied with precision [3]. This work motivated new theoretical treatments of this striking effect.

- Concentration Field in Traveling-Wave and Stationary Convection in Fluid Mixtures. Associated with TW convection in mixtures are three fields, describing velocity, temperature and concentration. The project developed ways to measure the concentration field [4], which motivated theoretical models of this effect.

- Eckhaus Instability for Traveling Waves. This important instability occurs when the system is confined in a one-dimensional geometry and the Rayleigh number (i.e., the scaled temperature difference across the layer) is reduced. We studied this instability for the important case where the pattern was composed of traveling waves [5].

- Dynamics of Two-Dimensional Traveling-Wave Convection Patterns. Research on this topic comprised a major fraction of the effort. We first characterized disordered patterns and their relaxation to more ordered states [7, 11]. The next step in the research was our discovery that we could measure with precision the phase field associated with these traveling wave patterns, and that they could be described in terms of topological phase defects. A description of the dynamics was then possible in terms of the motions of the phase defects [8,9,13]. The final stage of this research involved studying the influence of lateral boundaries on the patterns and understanding how to build this effect into the phase-defect description [14,15].

- Reflection of Nonlinear Waves from a Domain Boundary. In this study, we examined the reflection coefficient of waves at a domain boundary [10].

3.2 Other phenomena in ethanol-water mixtures

- Transition Between Curved and Angular Textures in Binary Fluid Convection. At the transition from traveling-wave to stationary convection, the rolls have a rectilinear nature, joining at domain boundaries with very small intervals of high curvature. As the Rayleigh number is increased further, the curvature decreases significantly. We studied this effect and built a simple analytic model to characterize the transition [6].

---

1 Numbers refer to the papers listed in Section 5.1
• *Convective Instability in Mixture Heated from Above.* We discovered a new effect when the binary fluid mixtures are heated from above [12]. While a simple, homogeneous fluid would be stable in this situation, ethanol-water mixtures exhibited a random pattern of isolated lines of flow, reminiscent of the phenomenon of so-called “salt fingering” in saline solutions. We characterized many aspects of this new phenomenon.

4. **Training of technical personnel**

4.1 **Doctoral students**

Steve Y. Yamamoto (Ph.D. 1994)
Keith D. Eaton (Ph.D. 1995)
Arthur La Porta (Ph.D. 1996)
Roman Sokolov (Ph.D., anticipated 2004)

4.2 **Postdoctoral Researchers**

Daniel R. Ohlsen (1989-91)
Arthur La Porta (1996-97)

5. **Publications**

5.1 **Articles in Refereed Journals**


5.2 Conference Proceedings


3. 2-D Traveling-Wave Patterns in Binary Fluid Convection, C. M. Surko and A. La Porta, *Proc. of the 14th Symposium on Energy Engineering Sciences* (DOE Office