Final Report
Apparatus for real-time acoustic imaging of Rayleigh-Bénard convection

Principle Investigator: Kerry Kuehn
Wisconsin Lutheran College, Milwaukee, WI 53226
Budget Period: From 08/15/2004 Thru 02/14/2008
DOE Award No. DE-FG02-04ER46166
Unexpended funds: $63,496.00

October 28, 2008

Contents

1 Apparatus design, construction and validation

We have successfully designed, built and tested an experimental apparatus which is capable of providing the first real-time ultrasound images of Rayleigh-Bénard convection in optically opaque fluids confined to large aspect ratio experimental cells. A detailed description of the apparatus, shown in Fig.1, can be found in our publication in the *Review of Scientific Instruments* [2, 3]. The apparatus employs a modified version of a commercially available ultrasound camera to capture images (30 frames per second) of flow patterns in a fluid undergoing Rayleigh Bénard convection. In particular, the apparatus is used to visualize the lateral variation of the temperature dependent speed of sound in the convecting fluid *via* refraction of acoustic plane waves passing vertically through the fluid layer.

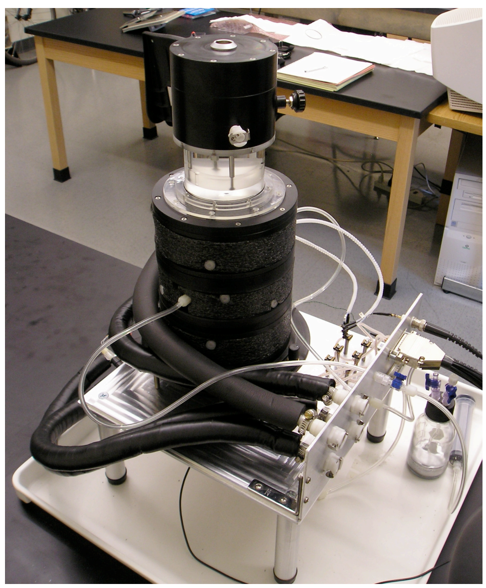

Figure 1: A photograph of the assembled apparatus.

The apparatus was validated by observing convection rolls in 5cSt polydimethylsiloxane (PDMS) polymer fluid (Dow Corning 200 fluid). These results were presented in a talk by the PI at the March Meeting of the American Physical Society [4]. Shown in Fig. 2 are two ultrasound images of PDMS confined to a thin cylindrical cell having an aspect ratio $\Gamma = 40.5$. Part (a) of the figure depicts the uniform conductive state, below the onset of convection. Just below, in part (b) of the figure, is shown the convective state. In both cases, the average fluid temperature was 28.5 C and the Prandtl number was 67.8. The short tick marks along the horizontal and vertical axes indicate lateral distances in units of the cell height, d. To the immediate right of images (a) and (b) are shown their respective power spectral densities. The axes of the computed power spectral density indicate the cartesian components of the wavenumber, k. The lack of structure in the power spectral density of image (a) reflects a uniform conductive state. The (black) peak in the power spectral density of image (b) reflects the appearance of straight convection rolls at the indicated value of k.

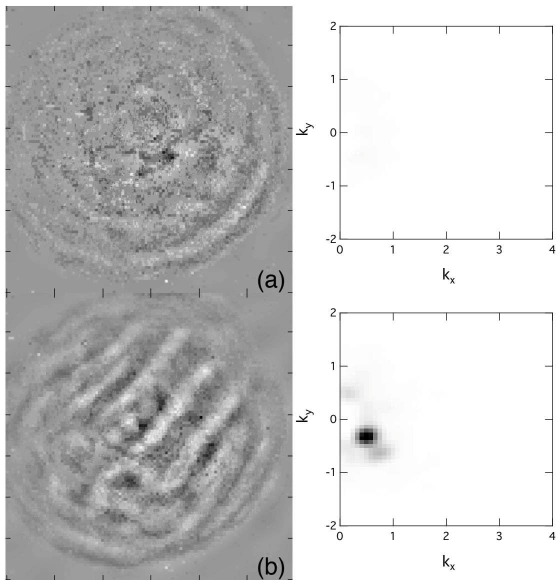

Figure 2: The onset of straight convection rolls in 5 cSt PDMS with $Pr = 67.8$. (a) $\Delta T = 3.22$ C and $Ra = 910$. (b) $\Delta T = 10.89$ C and $Ra = 3082$.

2 Mercury studies

Our first objective, after having built the apparatus, was to use it to study the sequence of transitions from diffusive to time–dependent heat transport in liquid mercury. The aim was to provide important information on pattern formation in the largely unexplored regime of very low Prandtl number fluids.

We have utilized our ultrasound camera to extensively study liquid mercury. We have confined the liquid mercury to (i) cylindrical cells with aspect ratios Γ =23.1, 26.8, and 31.0, and (ii) a rectangular cell with aspect ratio $\Gamma = 8 \times 2$. We have explored Rayleigh numbers in the range $0 < \mathrm{Ra} < 3053$; the Prandtl number of the liquid mercury was $\mathrm{Pr} = 0.034$. Based on the theoretical stability diagram for liquid mercury, we anticipated that straight rolls should be stable over a range of Rayleigh numbers, between 1708 and approximately 1900. Thus, in our most commonly employed cell, we anticipated straight rolls to be stable when the temperature difference across the cell was between 10.6 and 11.7 C, giving a stability range of approximately 1.1 C.

Though some of our power spectral densities were suggestive of the existence of weak convection, we have been unable to unambiguously visualize stable convection rolls above the theoretical onset of convection in liquid mercury. In what follows, we present a number of possible reasons for our inability to observe stable convection rolls above onset.

It is possible that the experimental conditions were such that straight rolls have not been formed, because either (i) the cell is insufficiently parallel, or (ii) the thermal gradients within the cell are insufficiently regulated. Regarding point (i), we have utilized both optical interferometric techniques and a sensitive micrometer to verify that the sapphire endplates of our experimental cells are parallel to within 2% of the cell height. This was sufficiently parallel to allow for stable convection roll formation in both PDMS and EFH1 ferrofluid (see Secs. 1 and 3 of this report). Regarding point (ii), the *vertical* temperature gradient in the cell was regulated to better than 10 thousandth of a degree Celsius. *Horizontal* temperature gradients in the sapphire endplates were likely small, since the thermal conductivity of sapphire is almost an order of magnitude larger than that of liquid mercury; it is likely that any horizontal temperature gradients are most pronounced near the cell edges due to the different thermal conductivities of the acetal sidewall and the liquid mercury. But even in the presence of such "sidewall forcing", one would still expect to realize convection rolls, albeit concentric circular ones instead of straight ones.

It is also possible that convection rolls formed in our cell, but that they were not discernible due to limitations on (i) the spatial resolution, or (ii) the sensitivity of our ultrasound camera. Regarding point (i), the wavelength of the 5 MHz ultrasound produced by our transducer is $\lambda \approx 0.3$ mm in liquid mercury at the temperatures employed. Thus the diffraction limit should not be an issue in resolving convective structures of the order of the cell height, $H \approx 4$ mm. Regarding point (ii), the more likely explanation: it is possible that the horizontal spatial variations of the (acoustic) index of refraction caused by fluid convection are so small that the rolls are simply indiscernible. In liquid mercury, the speed of sound temperature coefficient $(-\frac{1}{v}\frac{dv}{dt})$ is of the order 10^{-4} K^{-1}. Thus, the speed of sound varies within liquid mercury, during convection, by approximately 1 part in 1000. By contrast, in PDMS, the speed of sound temperature coefficient is $3 \times 10^{-3}\mathrm{K}^{-1}$. So during convection, the speed of sound varies within PDMS by approximately 3 parts in 100, which is a factor of 30 larger than in liquid mercury. Currently, we are seeking ways to increase the sensitivity of our apparatus, such as (i) improving the acoustic impedance matching between our materials in the ultrasound path and (ii) reducing the noise level in our acoustic images due to turbulence and cavitation in the cooling fluids circulating above and below our experimental cell.

Finally, if we are able to convincingly improve the sensitivity of our apparatus, and we still do not observe stable convection rolls in liquid mercury, then it may be the case that the theoretical stability diagram requires revision. In that case, either (i) straight rolls are not stable in a large aspect ratio cell at the Prandtl numbers associated with liquid mercury, or (ii) they are stable, but not in the region of the stability diagram which has been studied by this experimenter.

3 Ferrofluid studies

Our second objective was to use the apparatus to study other optically opaque fluids. To this end, we have obtained the first ultrasound images of Rayleigh-Bénard convection in a ferrofluid (EFH1), and are presently preparing a manuscript for publication [1]. The ferrofluid which we used was a colloidal dispersion comprised of magnetite particles (3-15% by volume) and oil soluble dispersant (6-30% by volume) suspended in a carrier liquid (55-91% by volume). We have confined the ferrofluid to a cylindrical cell ($\Gamma = 40.5$) and obtained images for Rayleigh numbers in the range $0 < \mathrm{Ra} < 3827$. In our forthcoming publication, we intend to report the variation of the power spectral density of the induced convection pattern(s) as a function of the Rayleigh number of the fluid.

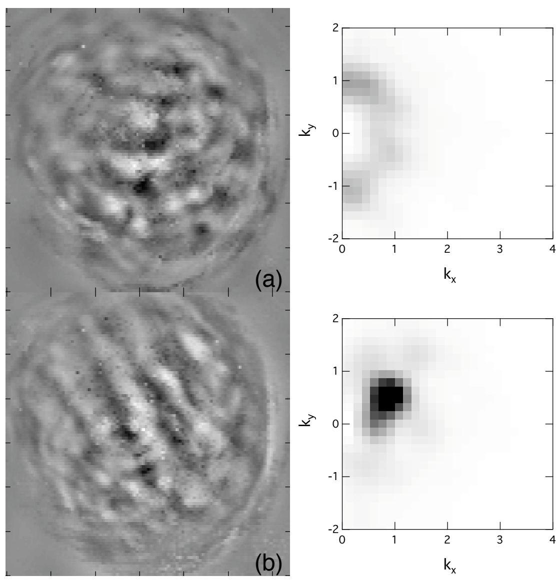

Figure 3: Convective structures above onset in EFH1 ferrofluid with $Pr = 101.2$. The cell was tilted by 2.89 degrees. (a) $\Delta T = 15.44$ C and $Ra = 1986$. (b) $\Delta T = 26.89$ C and $Ra = 3460$.

Shown in Fig. 3 are some ultrasound images of the EFH1 ferrofluid. For this particular set of experiments, the convection cell was tilted by 2.89 degrees so as to induce a large scale lateral flow and to facilitate roll formation; such tilting was not required to form stable convection rolls. Part (a) of the figure depicts a state of cellular convection just above onset. Part (b) of the figure depicts a straight-roll convection state at somewhat higher Rayleigh number. For these particular experiments, the average fluid temperature was 29.9 C and the Prandtl number was 101.2. As in Fig. 2, to the immediate right of each image is shown a grayscale image of its computed power spectral density. The broad peak near $k = 1$ in the power spectral density associated with image (a) reflects the lack of orientational order observed in the cellular convection state, whereas the localized peak in the power spectral density associated with image (b) reflects the distinct straight roll pattern.

4 Undergraduate training

This project provided a vehicle for the scientific training of five undergraduate research assistants during the past four years. It allowed students at Wisconsin Lutheran College, a small undergraduate liberal arts college in Milwaukee, to become directly involved in a significant scientific project from its inception through publication of scientific results. Below are short biographies of each undergraduate student's involvement and their current status.

1. Nathan Finke, who graduated from the College with a mathematics major, worked on designing and building the thermometry and the electronics for the data acquisition system. He is currently a graduate student in the Department of Mathematics at The College of William and Mary.

2. Jonathan Polfer, who graduated from the College with a major in theology and a minor in computer science, designed the automated computer data acquisition software and provided extensive computer support. He has presented his work in oral and poster format at two undergraduate research symposia [5, 10]. The work which he did on this project had a significant impact on the hiring decision of his present employer; he is currently working as an engineer at Abbott Laboratories in Abbott Park, Illinois.

3. Joanna Furno, who graduated from the College with a mathematics major, built and tested the thermometers for the temperature regulations system, and ran initial tests on the newly designed apparatus. Inspired by work on this project, she also co-authored a theoretical paper with the Principle Investigator on tidal instabilities in fluids generated by multiple gravitational sources [6, 7]. She is currently a graduate student in the Department of Mathematics at the University of North Carolina in Chapel Hill.

4. Dan Sanfelippo learned how to do image processing and to use a computer aided design program to make three dimensional models of components for our experimental apparatus. He also learned how to operate the College's new CNC milling machine to build apparatus parts. He expects to graduate from the College next year with a degree in biology or biochemistry.

5. Mike Schultz did a wide variety of laboratory work including apparatus maintenance, data collection, and software support. He completely revised and updated the data acquisition system designed by Jonathan Polfer so that we could run the experiment using a Mac rather than on a PC. He expects to graduate in December with a degree in Computer Science, and has been offered an engineering position in the field of diagnostic medical imaging.

5 Research infrastructure development

The funding of this project has strengthened the research and teaching infrastructure at the Wisconsin Lutheran College in three major ways.

1. **Major scientific equipment acquisition** The project has funded the PI and his students in the design and construction of a major piece of scientific apparatus which is capable of performing novel studies of Rayleigh-Bénard convection in opaque fluids. With the acquisition of this apparatus, we are able to embark on a broad research program to study problems in pattern formation in alloys, ferro-fluids, opaque gels, and liquid metals under thermal or magnetic stresses.

2. **Fluid dynamics laboratory setup** This project has allowed the PI to purchase auxiliary equipment necessary for establishing a fluid dynamics research laboratory at the College. This laboratory includes a data acquisition system, power supplies, laboratory tools, a stock of electronic and plumbing components and essential laboratory chemicals and cleaning supplies.

3. **Machine shop setup** This project has served as an impetus for the College to invest in a new machine shop in the basement of the Science Building at the College in order to support this, and other, scientific projects at the College. The machine shop contains several pieces of equipment, including a computer-controlled milling machine, which was used extensively by the PI and his students in building the experimental apparatus. The machine shop also contains a lathe, band saw, drill press, welding station, and assorted tools.

6 Public outreach

The PI has presented work funded by this grant at physics and engineering colloquia at a nearby university [11, 13] and at the keynote presentation at an undergraduate research symposium at Wisconsin Lutheran College [9]. Also, the work was featured in local magazine and newspaper articles [8, 12], and is described on the PI's research webpage (`http://faculty.wlc.edu/kuehn/Research/Research.html`). Such scientific outreach serves to advance the cause of science by making it interesting and accessible to a wider audience, and to bring attention to the work done by the Office of Basic Energy Sciences of the Department of Energy.

References

[1] K. Kuehn. Ultrasound images of the onset of Rayleigh-Bénard convection in EFH1 ferrofluid. Manuscript in preparation.

[2] K. Kuehn, J. Polfer, J. Furno, and N. Finke. Apparatus for real-time acoustic imaging of Rayleigh-Bénard convection. *Review of Scientific Instruments*, 78(11):113704, November 2007.

[3] K. Kuehn, J. Polfer, J. Furno, and N. Finke. Apparatus for real-time acoustic imaging of Rayleigh-Bénard convection. *ArXiv e-prints*, July 2007. `http://arxiv.org/abs/0707.3293v1`

[4] K. Kuehn, J. Polfer and J. Furno. Apparatus for real-time acoustic imaging of Rayleigh-Bénard convection. *APS Meeting Abstracts*, March 2007. `http://meetings.aps.org/link/BAPS.2007.MAR.W30.2`

[5] J. Polfer. Porting a Device Driver from a Driver Development Kit. *Seventh Annual Undergraduate Research Symposium*, Milwaukee, WI, April, 2007.

[6] J. Furno and K. Kuehn. Tidal pattern instabilities on multi-moon planets. *Icarus*, 189:246–255, July 2007.

[7] J. Furno and K. Kuehn. Tidal pattern instabilities on multi-moon planets. *ArXiv e-prints*, January 2007. `http://arxiv.org/abs/physics/0701301v1`

[8] M. Hrodey. Learning Curve. Students aren't just learning from professors, but helping them, too. *Milwaukee Magazine*, 94, August 2007.

[9] K. Kuehn. Pattern Formation in Nature. Keynote Presentation, *Sixth Undergraduate Research Symposium*, Milwaukee, WI, April 29, 2006.

[10] J. Polfer. Computer Temperature Control of a Rayleigh-Bénard Convection Appatus. Poster presentation, *Sixth Annual Undergraduate Research Symposium*, Milwaukee, WI, April 29, 2006.

[11] K. Kuehn. Real-Time Acoustic Imaging of Rayleigh-Bénard Convection in Liquid Mercury. *Marquette University Physics Colloquim*, Milwaukee, WI, February 2006.

[12] Kuehn Garners $256,000 Grant to Study Thermal Convection in Liquid Metals. *Today Magazine*, 11, November 2004.

[13] K. Kuehn. Real-Time Acoustic Imaging of Rayleigh-Bénard Convection in Liquid Mercury. *Marquette University Engineering Colloquium*, Milwaukee, WI, 2004.