ULTRASOUND MEASUREMENT OF TEMPERATURE PROFILES IN CONVECTING OPAQUE FLUIDS

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ABSTRACT

An ultrasonic technique has been developed to non-intrusively measure temperature fields in convecting opaque fluids. As many industrial processes involve opaque fluids with imposed thermal gradients it is important to be able to accurately and simply determine their temperature distributions. However, most current diagnostic techniques involve optical methods, or require mounting probes inside the fluid; these methods either fail altogether in opaque fluids, or require significant invasion of the flow and/or modification of the walls of the container to allow access to the fluid. We have used the temperature dependence of sound velocity to probe the thermal fields of convecting opaque fluids non-intrusively and without the use of seed particles. The technique has been validated by comparing simultaneous ultrasound measurements and visualization using a suspension of thermochromic liquid crystals in a transparent convection cell filled with glycerol. Subsequently we constructed and calibrated an array of ultrasound transducers, relying upon the experimentally determined variation of sound speed in mercury with temperature, and used the array to measure temperature distributions in a mercury-filled Rayleigh-Bénard convection cell. The measurements of cell wavelength and onset Rayleigh number are close to the theoretically predicted values. Limitations and potential improvements will be described.

1. INTRODUCTION AND METHOD

1.1 Background

The buoyancy driven flows of transparent fluids in systems with rigid boundaries at the top and bottom (Rayleigh-Bénard convection) have been extensively studied, both for their potential applications and as beautiful examples of pattern formation in non-equilibrium systems (see Cross and Hohenberg (1993) for a review of convection in single layers and related pattern forming systems). However, most such work has concerned the convection of transparent fluids, owing partially to the available diagnostic tools. Relatively non-intrusive velocity and temperature measurements typically rely on optical techniques, and hence are useful only with transparent fluids. Laser Doppler velocimetry (LDV) and particle imaging velocimetry (PIV) rely on the addition to the flow of small seed particles. A recent development is the ultrasound Doppler velocimeter (Takeda (1986)). As with LDV, it relies on seed particles to scatter Doppler shifted sound back to the detector. In contrast with LDV, Doppler ultrasound works in both transparent and opaque fluids. A very different type of approach, limited to transparent fluids, is to use the variation of the index of refraction of the fluid with temperature to visualize the thermal field through interferometric, Schlieren or shadowgraph techniques (Goldstein (1983), Prakash and Koster (1996)). In each case the result is a 2D map related to the average of the temperature field along the line of observation. An alternative approach, which is not limited to transparent fluids and does not require seeding, is to use hot-wire or hot-film probes (Blackwelder (1981)). Unfortunately, these probes can be quite invasive. Thus the options for studying opaque fluids such as liquid metals are limited, while the importance of studying their flows is clear; since their thermal properties are quite different from transparent fluids typically used, any attempt to use a transparent fluid to model the detailed flow properties of a liquid metal under thermal stress is doomed to failure. As many industrial processes involve opaque fluids, often in situations in which thermal gradients are important, the need for new diagnostic tools is apparent.

1.2 Experimental Technique

We have used ultrasound to detect the thermal fields of opaque fluids non-intrusively and without the use of seed particles. The technique relies upon the variation of sound speed with the temperature of the fluid. The use of sound speed to measure the temperature of a gas was apparently first proposed by Mayer (1873). The concept has been realized in a particular manner in large-scale gas systems (such as in the interiors of furnaces and boilers) by Morgan (1972), Dadd (1983), Green (1985), Bramanti et al. (1996), and Sielschott (1997). For work with a small laboratory scale apparatus we have adopted the pulse-echo ultrasound technique commonly employed for nondestructive testing of solids. Specifically, a very short ultrasound pulse traverses the fluid-filled chamber in a time determined by the chamber geometry and the average temperature of the fluid through which the pulse passes. We measure the time between the arrival of an echo pulse from the first wall/liquid interface and the arrival of a pulse from the second such interface, the one on the far side of the chamber. The measurement demands are stringent. Nevertheless, with high speed instrumentation we can detect the influence of the fluid temperature on the pulse travel time and thus obtain temperature measurements of the fluid interior. With the present system, spatial resolution of a few millimeters is achievable. Temperature resolution of a fraction of a degree C has been achieved. With an array of transducers a map of the thermal field over the chamber can be produced on a time scale short compared with many convective processes. While we cannot yet achieve the speed or resolution of optical systems, our approach is nonetheless quite adequate for many flow problems.

Figure 1 shows a typical experimental configuration. The contact transducer array, consisting of from 1 to 11 contact transducers (Panametrics M110, for example) arranged linearly, was connected to a Keithley model 7002 switcher, which, under computer control, can shift the electrical connection to the Panametrics pulser/receiver from one transducer to the next with approximately 0.15 s dead time. The output of the pulser/receiver is sent to a preamplifier, which allows us to adjust the voltage offset and gain so that the signal excursions are maximized within the input range of the Perkin-Elmer *Eclipse*, a very high speed signal averager. In the *Eclipse*, signals from a particular transducer accumulate until an averaged output can be transferred to the computer, and the switcher brings the next transducer online. The LabView program responsible for control of the data acquisition then finds the appropriate peaks in the averaged signal and stores their locations for additional processing after the data run is completed. It is possible to obtain a complete scan of the array, with 1024 pulses per transducer, in a few seconds. In addition to control of the data acquisition process, the computer is also responsible for setting the top and bottom plate temperatures, reading thermistor resistances in those plates, and controlling a traversing system that allows us to move the transducer array to provide a 2D thermal map of the chamber. Details of the basic concepts and early work on this technique are found in Fife et al. (2002).

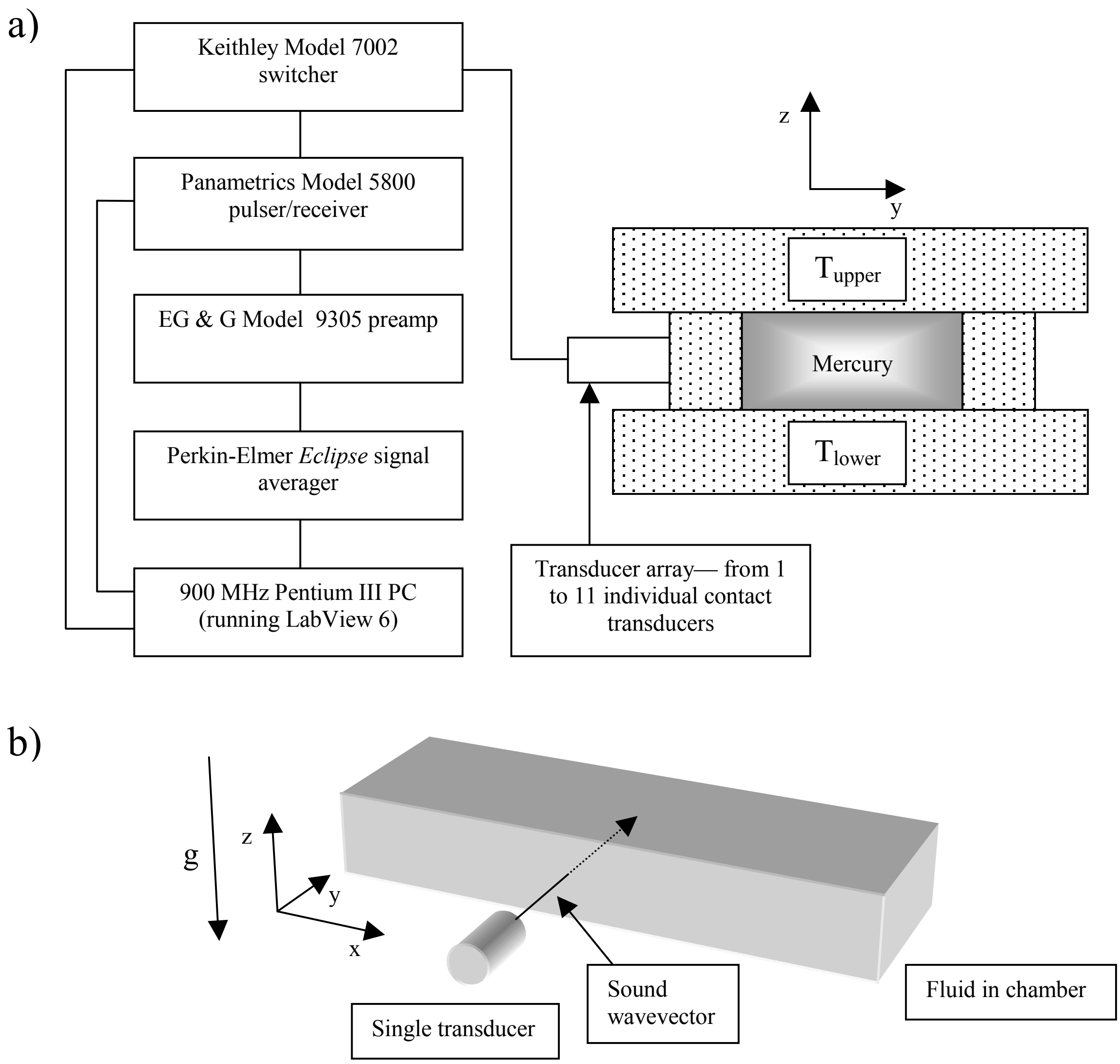

Figure 1. a) Schematic diagram of apparatus. b) Sketch of fluid chamber and its relation to gravity, a representative transducer, and the direction of sound propagation.

2. RESULTS

2.1 Emergence of Patterns

Using a mercury filled stainless steel chamber with depth (z direction) 13 mm, length (x direction) 77 mm, and width (along the direction of sound propagation as in Figure 1b)) 20 mm, we have measured the temperature profile along a line at mid-depth as a function of imposed vertical temperature gradient, heating from below. Figure 2 shows an example data run. At low temperature gradients the profile is essentially flat, uniform across the chamber and indicative of a purely conductive state. As the temperature gradient increases a pattern of rolls emerges, as indicated by the higher and lower temperature regions in the chamber. In this case, the final state consists of four convection rolls, with rising fluid in the chamber center and at either end.

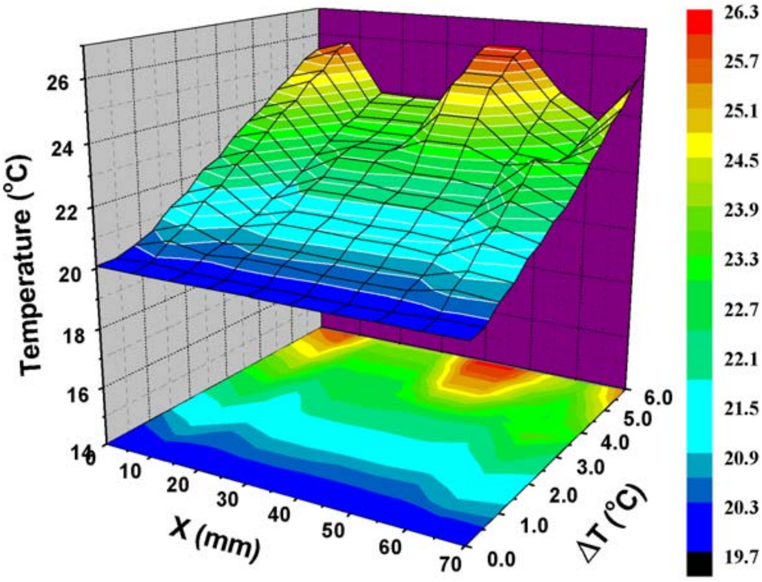

Figure 2. Temperature profile in mercury with increasing temperature gradient, measured at mid-depth along the chamber length.

For a fixed temperature gradient, it is possible to produce a 2D map of the temperature profile by moving either a single transducer or an array of transducers to a set of locations across the external vertical surface of the chamber. A typical result is shown in Figure 3 using a single XMS310 transducer, for an imposed temperature difference of 11.8 C.

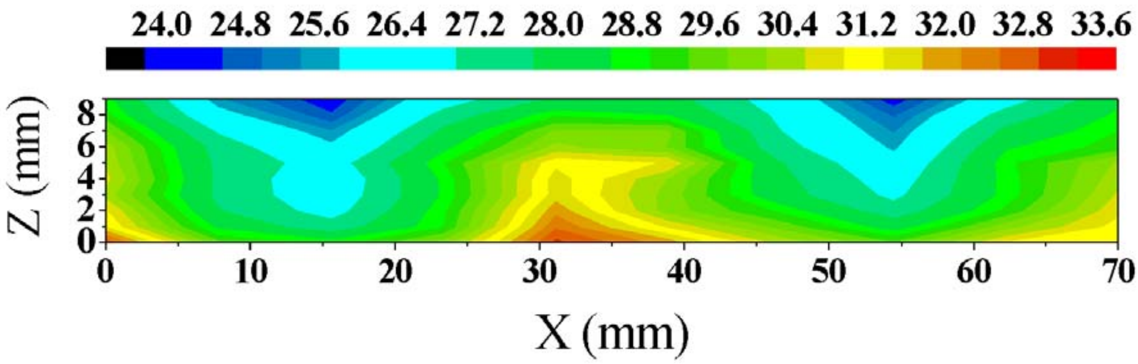

Figure 3. 2D temperature profile for ΔT = 11.8 C

2.2 Pattern Onset

In order to verify the onset of convection, which is predicted to be at a Rayleigh number of 1708 for an infinite system with conducting rigid top and bottom boundaries, we have measured the magnitude of the temperature perturbation as we slowly ramped up or down the imposed ΔT under computer control. The standard deviation of the temperature perturbation obtained from 11 transducers located along a line at mid-depth was plotted against Rayleigh number. It is clear from Figure 4 that an imperfect supercritical bifurcation is occurring at a Raleigh number comparable to the theoretical prediction, and that the result is reproducible over many different experimental runs.

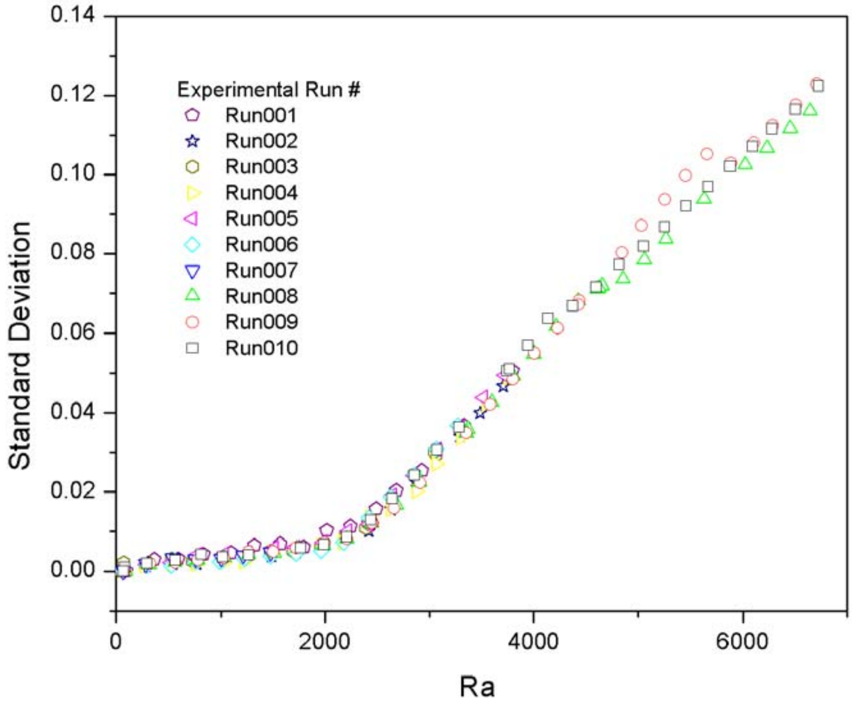

Figure 4. Standard deviation of the temperature profile as a function of Rayleigh number near convection onset

A further test of the technique's capability is provided by measurement of the pattern wavenumber near onset. Again, we have analyzed the data from a mid-depth temperature profile, specifically from run # 9 in the study above, and compared our wavenumber data with the neutral stability curve from Chandrasekhar, S. (1981). Our critical wavenumber, as shown in Figure 5, is quite close to the predicted value.

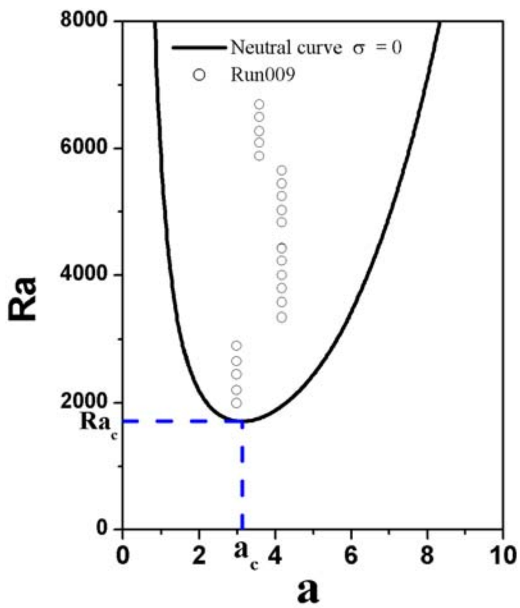

Figure 5. Stability diagram showing the critical Rayleigh number Ra_c, the critical wavenumber a_c, the theoretical neutral curve and measured wavenumbers from run 9

3. CONCLUSIONS

We have demonstrated the usefulness of ultrasound as a probe of the temperature field in liquid metals undergoing convection. The technique has sufficient sensitivity to detect the approximate onset of convection, and sufficient accuracy to yield predicted wavenumbers. We hope to extend this method to other situations in which the unique properties of liquid metals play a role in determining the flow behaviour.

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