

THERMAL IMAGING OF CONVECTING OPAQUE FLUIDS USING ULTRASOUND

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ABSTRACT

An ultrasound technique has been developed to non-intrusively image temperature fields in small-scale systems of opaque fluids undergoing convection. Fluids such as molten metals, semiconductors, and polymers are central to many industrial processes, and are often found in situations where natural convection occurs, or where thermal gradients are otherwise important. However, typical thermal and velocimetric diagnostic techniques rely upon transparency of the fluid and container, or require the addition of seed particles, or require mounting probes inside the fluid, all of which either fail altogether in opaque fluids, or necessitate significant invasion of the flow and/or modification of the walls of the container to allow access to the fluid. The idea behind our work is to use the temperature dependence of sound velocity, and the ease of propagation of ultrasound through fluids and solids, to probe the thermal fields of convecting opaque fluids non-intrusively and without the use of seed particles. The technique involves the timing of the return echoes from ultrasound pulses, a variation on an approach used previously in large-scale systems.^{1,2}

We initially validated our method by comparing ultrasound measurements with simultaneous visualization using thermochromic liquid crystals suspended in glycerol in a transparent convection cell. As a next step we assembled a linear array of Panametrics M110 ultrasound transducers and calibrated it using the experimentally determined temperature variation of sound speed in mercury. We then used this array to measure temperature profiles in a narrow (2 cm) and shallow (1.3 cm) stainless steel Rayleigh-Bénard convection cell filled with mercury. Figure 1 shows typical data. In this case the array of transducers was aligned with the long dimension of the chamber, and located at mid-height. The data output yields a temperature profile along the chamber, perpendicular to the imposed temperature gradient. The profile clearly reveals the formation of cells driven by natural convection as the temperature difference between the bottom and top plates was slowly increased from 0 to 1.0 °C, the final temperature corresponding to a Rayleigh number (Ra) of 7550.

Figure 2 is a 2D image of the thermal field in convecting mercury for an imposed vertical temperature difference of 5.8 °C (Ra = 43790). This image was obtained by translating one Panametrics V129, under computer control, from location to location across the outside of the chamber. The flow consists of four convection rolls. The warmer, rising plumes are in the middle and at either end, while the cooler, falling plumes are in between.

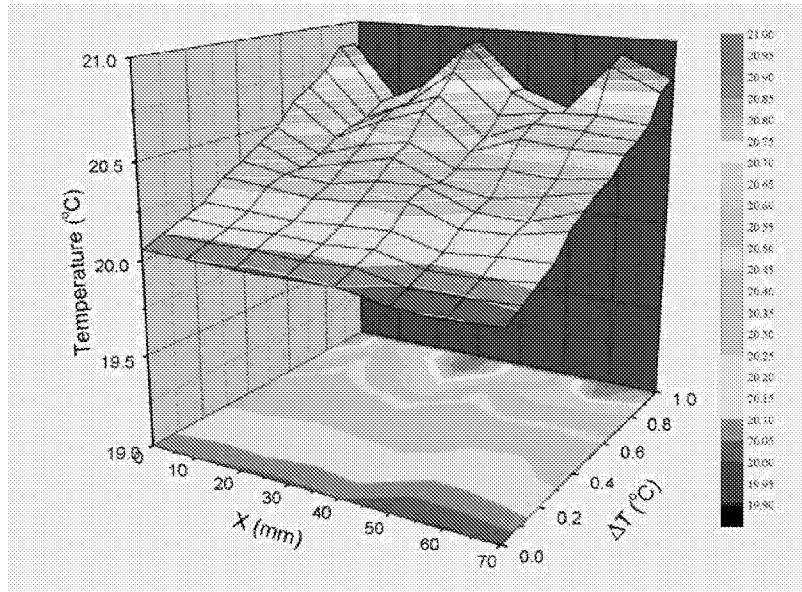


Fig. 1. Temperature profile evolution of Rayleigh-Bénard convection in mercury.

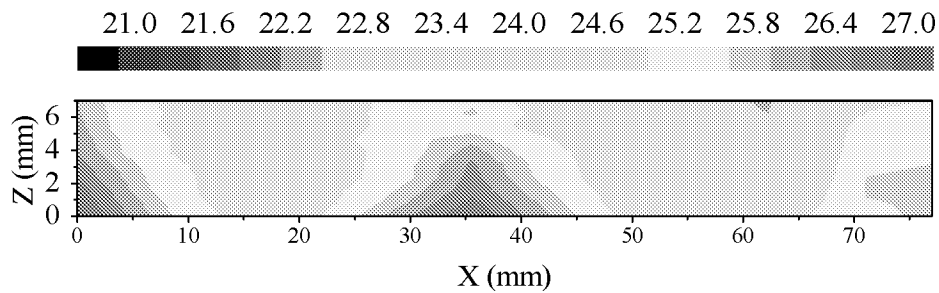


Fig. 2. 2D thermal image of convection in mercury.

Details of our technique, including its limitations and future prospects, will be presented.

This work was supported by NASA Microgravity Fluid Physics Program grant NAG 3-2138.

REFERENCES

- [1] Green, S. F., An Acoustic Technique for Rapid Temperature Distribution Measurement, *J. Acoust. Soc. Am.* 77, 759-763 (1985).
- [2] Bramanti, M., Salerno, E. A., Tonazzini, A., Pasini, S. and Gray, A., An Acoustic Pyrometer System for Tomographic Thermal Imaging in Power Plant Boilers, *IEEE Trans. Instr. Meas.* 45, 159-167 (1996).

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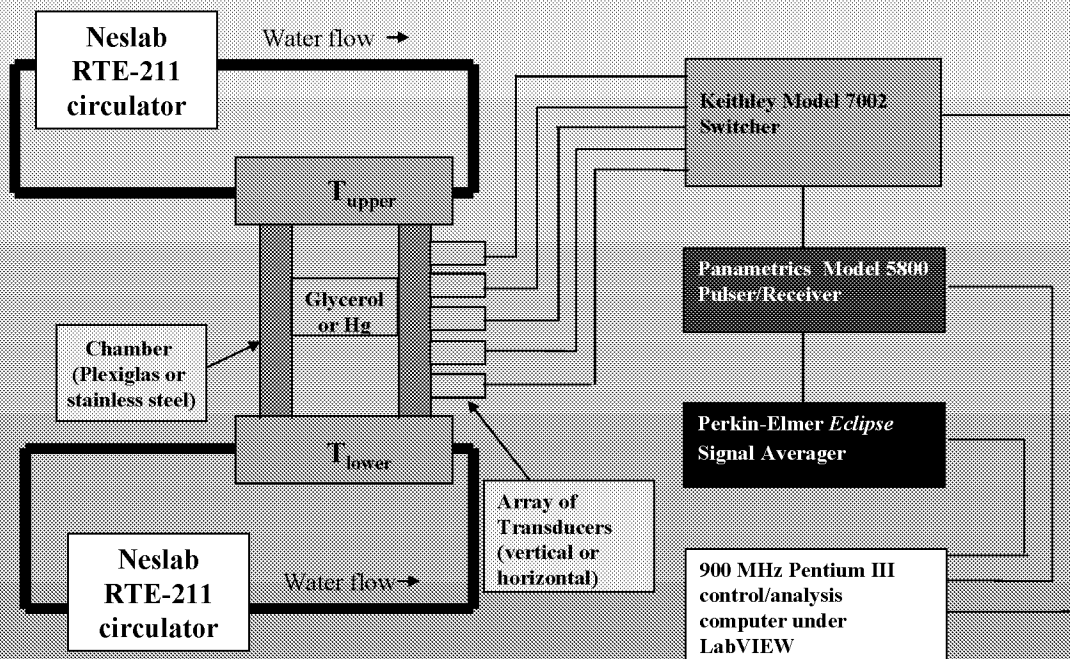


Supported by NASA Grant NAG3-2138

Abstract

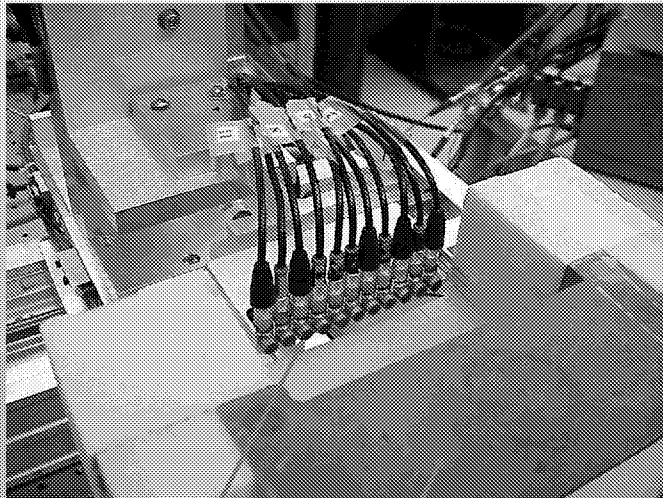
We have exploited the temperature dependence of sound velocity to measure the thermal fields in transparent and opaque fluids in a non-intrusive way. A chamber containing Glycerol undergoing Rayleigh-Bénard convection was probed with an ultrasound transducer operating in the pulse-echo mode. The times-of-flight for the ultrasound pulse to traverse the fluid at several transducer locations were converted into a temperature profile that is in qualitative agreement with simultaneous thermochromic liquid crystal visualization of the flow pattern, thereby validating the concept. 2D temperature profiles of a liquid metal (Mercury) filled stainless steel chamber have been obtained for a range of imposed temperature differences. These profiles clearly reveal the convection roll pattern.

Apparatus



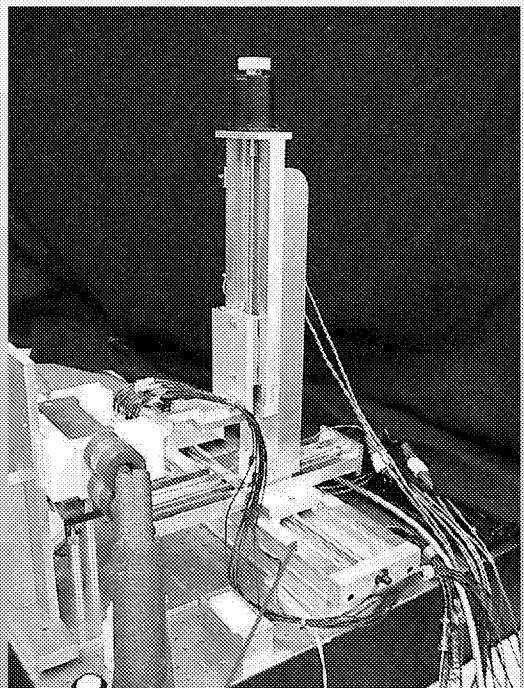
Note: Computer controlled 3-D traversing system moves transducer array to cover the chamber.

Apparatus (cont'd.)



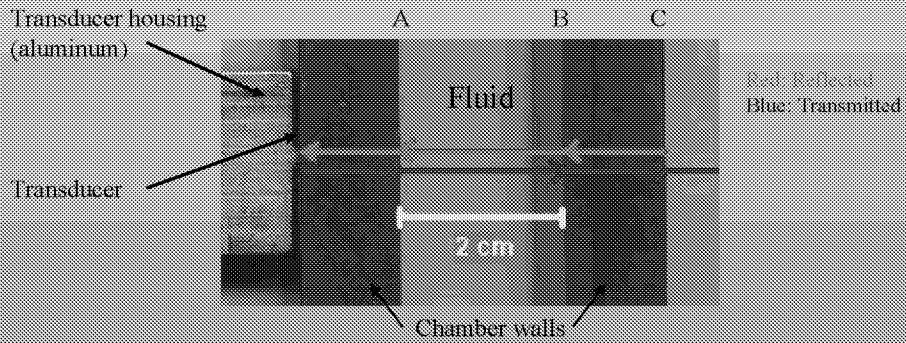
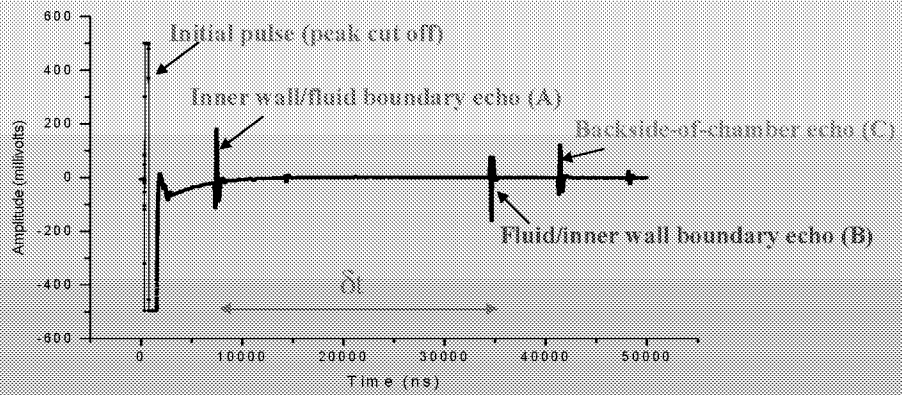
Convection cell

Ultrasound transducer array (eleven Panametrics V129 contact transducers)



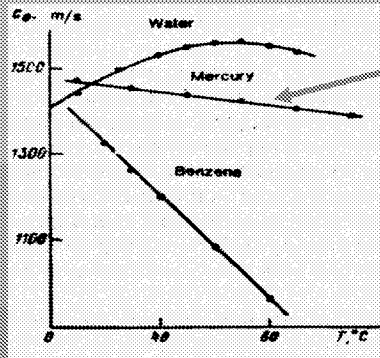
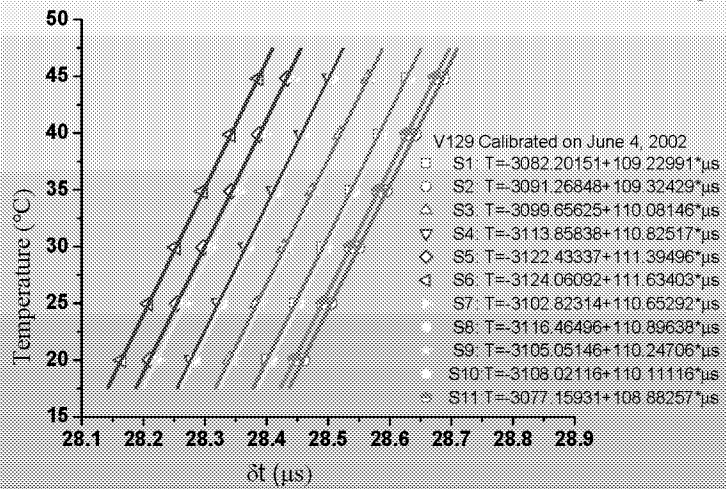
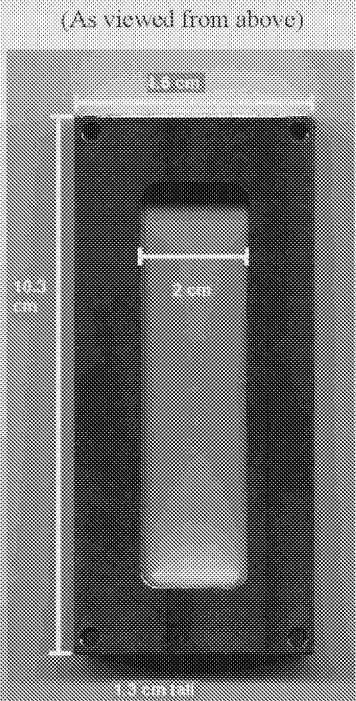
3-D traversing system

Example Signal and Its Origin



By measuring δt and knowing the size of the chamber and the sound velocity, we can deduce the *average temperature of the fluid along that path*.

Chamber Dimensions and Transducer Calibration for Hg

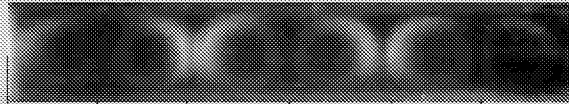


Published variation of sound speed in Hg with temperature (V. A. Shatalov, 1988, *Fundamental Physics of Ultrasound*)

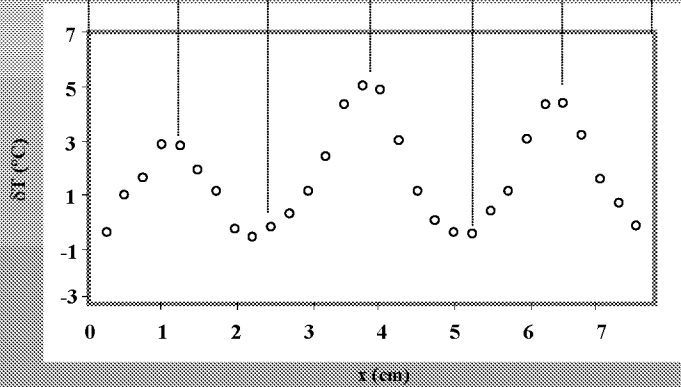
Proof of Concept

We have used a standard visualization technique on a transparent fluid to compare with the ultrasound results.

We seeded glycerol contained in a Plexiglas wall chamber with thermochromic liquid crystals (Hallcrest R29C1W), then heated from below to form Rayleigh-Bénard convection rolls:

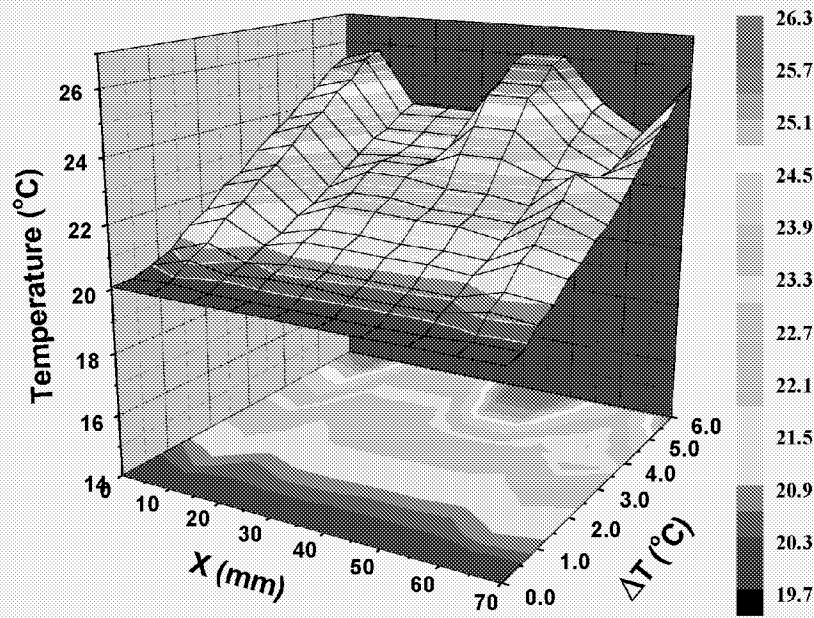


We simultaneously obtained ultrasound data from a single transducer moved manually from point to point, showing a strong correlation between the two techniques:

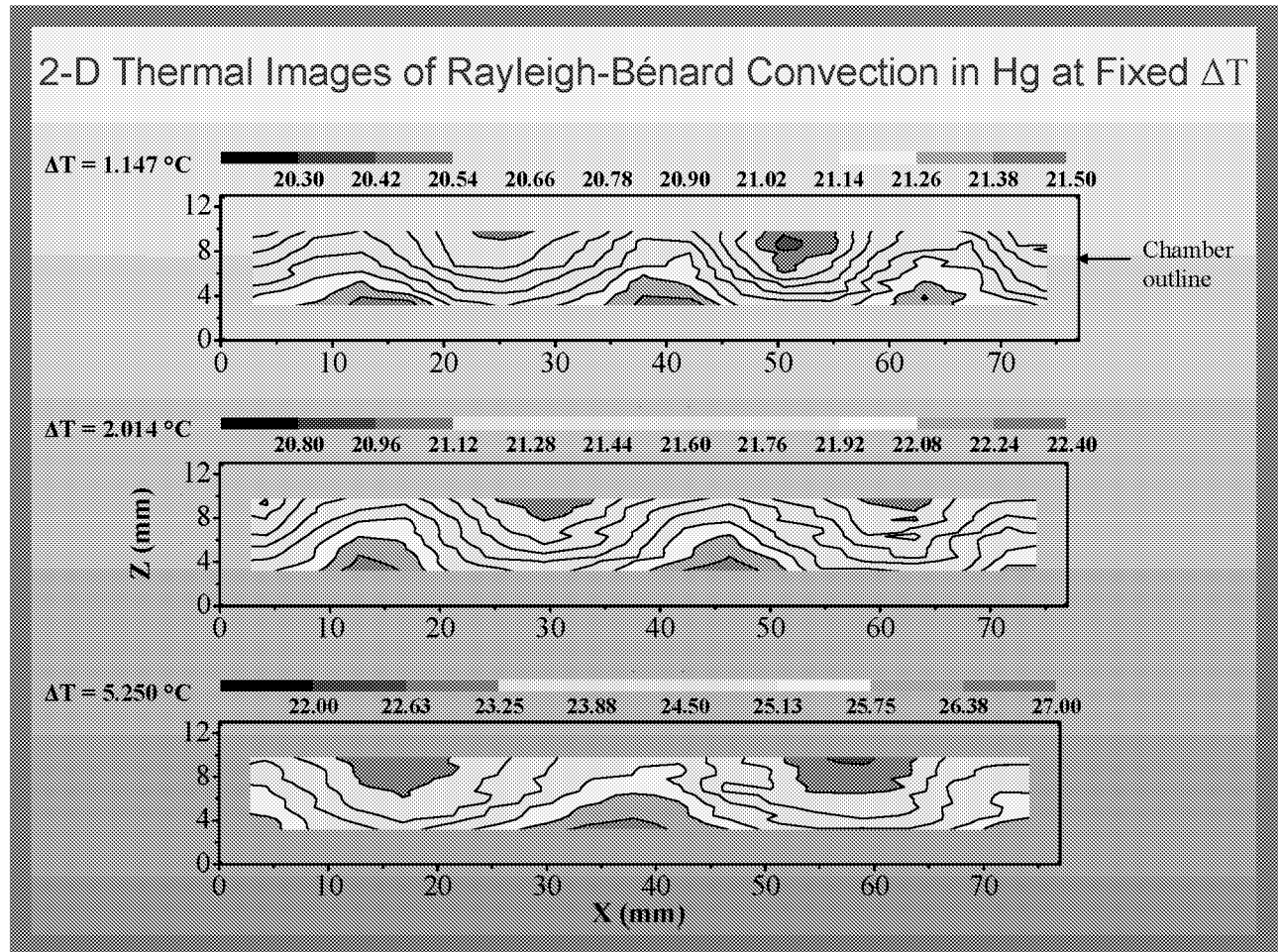


... thus the method is validated.

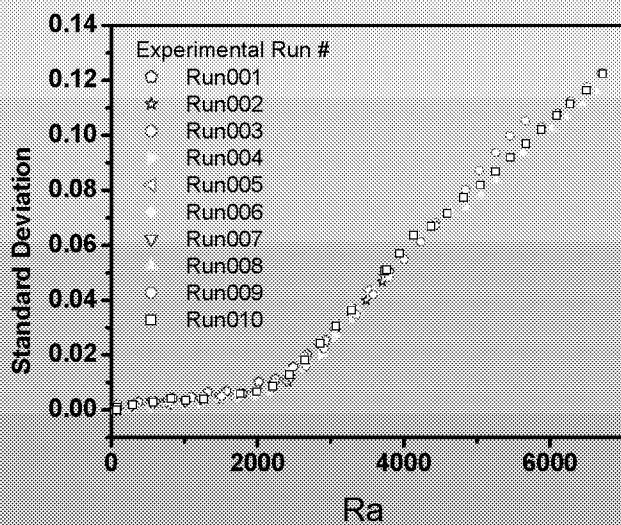
Temperature Profile Evolution of Rayleigh-Bénard Convection in a Liquid Metal (Hg) With Slowly Ramped ΔT



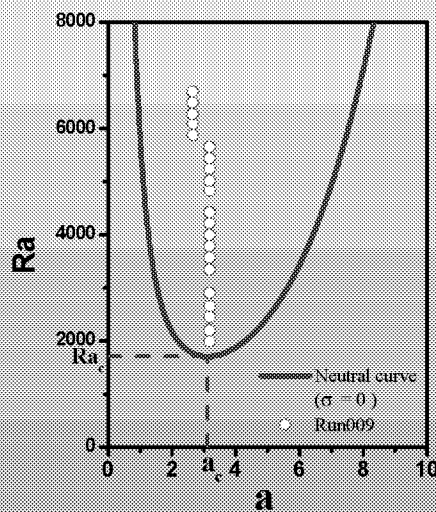
Slowly increasing temperature gradient ΔT (0.005°C/minute). Temperature measured at several locations along the chamber length on a line at mid-depth.



Onset of Rayleigh-Bénard Convection in Mercury



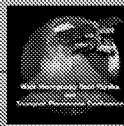
Standard deviation of the temperature profile as a function of Rayleigh number near convection onset.



Stability diagram showing the critical Rayleigh number Ra_c , the critical wavenumber a_c , the theoretical neutral curve (Chandrasekhar, S. (1981) *Hydrodynamic and Hydromagnetic Stability*), and measured wavenumbers.

Conclusions and Future Work

- We have successfully demonstrated the use of ultrasound to measure temperature profiles in transparent and opaque fluids in laboratory scale convection with small imposed temperature gradients, and have shown good agreement with predictions and comparison techniques.
- We will use this technique in the future for crystal solidification, ferrofluids, and other physically interesting flows.



**Sixth Microgravity Fluids Physics
and Transport Phenomena Conference**
August 14-16, 2002