THERMAL FIELD IMAGING USING ULTRASOUND

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It is often desirable to be able to determine the temperature field in the interiors of opaque fluids forced into convection by externally imposed temperature gradients. To measure the temperature at a point in an opaque fluid in the usual fashion requires insertion of a probe, and to determine the full field therefore requires either the ability to move this probe or the introduction of multiple probes. Neither of these solutions is particularly satisfactory, although they can lead to quite accurate measurements. As an alternative we have investigated the use of ultrasound as a relatively non-intrusive probe of the temperature field in convecting opaque fluids. The temperature dependence of the sound velocity can be sufficiently great to permit a determination of the temperature from timing the traversal of an ultrasound pulse across a chamber. In this paper we will present our results on convecting flows of transparent and opaque fluids.

Our experimental cells consist of relatively narrow rectangular cavities made of thermally insulating materials on the sides, and metal top and bottom plates. The ultrasound transducer is powered by a pulser/receiver, the signal output of which goes to a very high speed signal averager. The average of several hundred to several thousand signals is then sent to a computer for storage and analysis. The experimental procedure is to establish a convective flow by imposing a vertical temperature gradient on the chamber, and then to measure, at several regularly spaced locations, the transit time for an ultrasound pulse to traverse the chamber horizontally (parallel to the convecting rolls) and return to the transducer. The transit time is related to the temperature of the fluid through which the sound pulse travels. Knowing the relationship between transit time and temperature (determined in a separate experiment), we can extract the average temperature *across* the chamber at that location. By changing the location of the transducer it is then possible to find the average temperature at different locations along the chamber, thereby determining the temperature profile along the system. (In the future we will construct an array of transducers. This will give us the capability to determine the temperature profile much more rapidly than at present, an important consideration if time-dependent phenomena are to be studied.)

To validate our procedure we introduced encapsulated liquid crystal particles into glycerol. The liquid crystal particles' color varies depending on the temperature of the fluid. A photograph of the fluid through transparent sidewalls therefore gives a picture of the temperature field of the convecting fluid, independent of our ultrasound imaging. A representative result is shown in the Figure 1, which reveals a very satisfying correspondence between the two techniques. Therefore we have a great deal of confidence that the ultrasound imaging approach is indeed measuring the actual temperature profile of the fluid. The technique has also been applied to convecting liquid metal flows, and representative data will be presented from those experiments as well.

[1] Supported by NASA NAG3-2138.

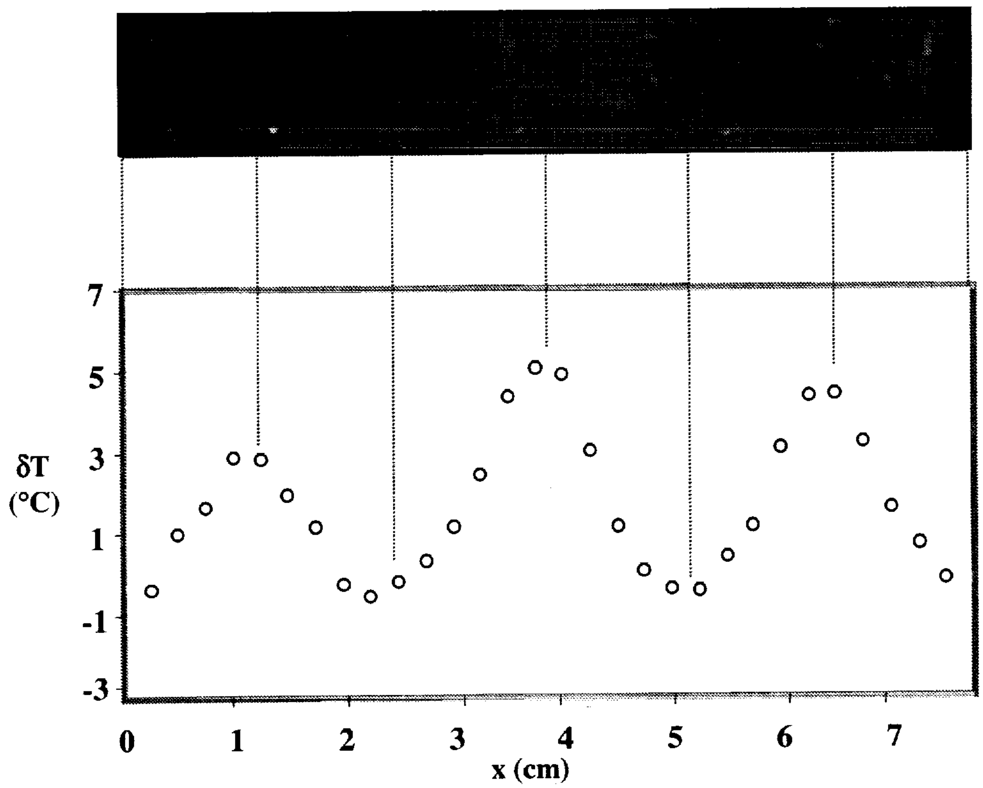

Figure 1: Relation between temperature field in convecting glycerol as revealed by suspended encapsulated liquid crystals, and a temperature profile from ultrasound transit times.

Ultrasound Imaging of Thermal Fields

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Aim of the work

* Interesting flows of opaque fluids abound: crystal growth, molten metals, polymers

* Current techniques and their limits:

  - Optical techniques (transparent fluids)

  - Thermistors, thermocouples, hot wire probes (invasive and local)

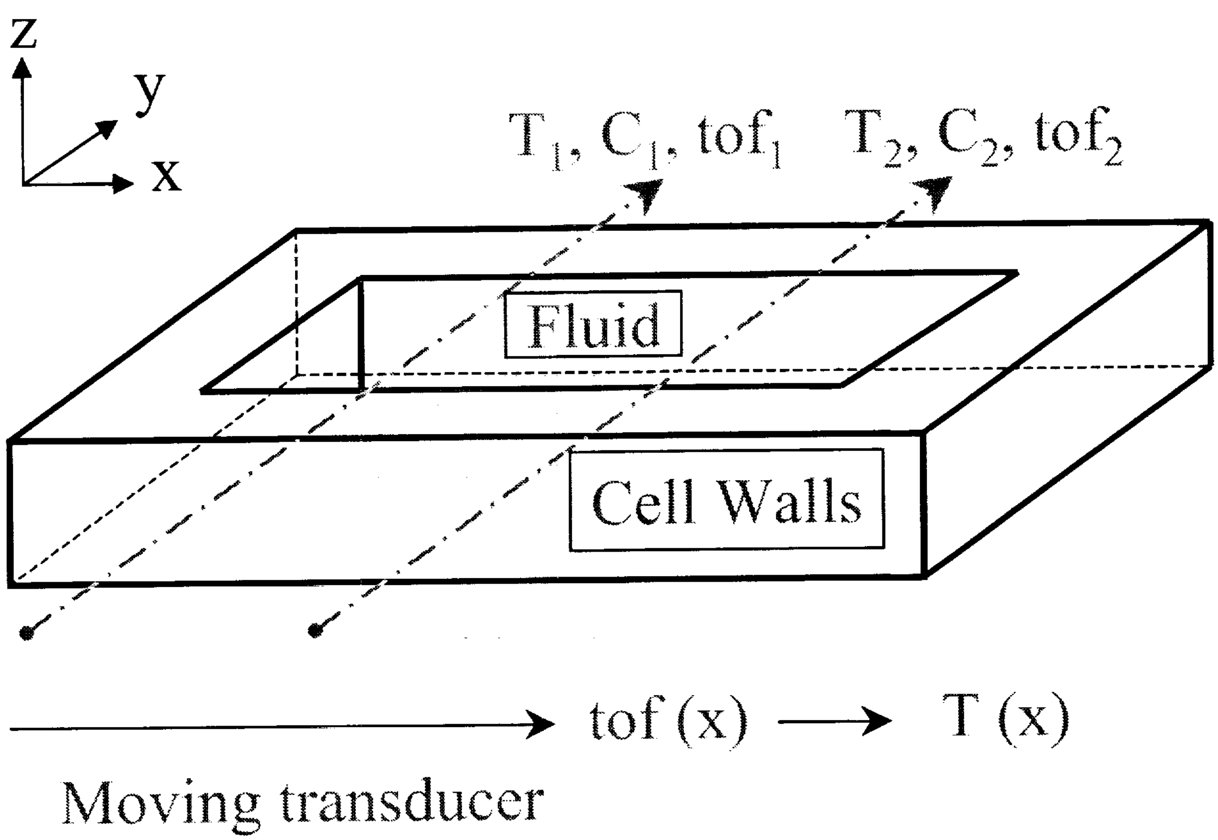
  - Ultrasound velocimetry (requires seeding)

  - X-rays (requires very thin samples)

Therefore, attempt to use
use ***ultrasound*** to map ***thermal fields***

The Concept

Sound velocity is a function of temperature along the path of sound propagation

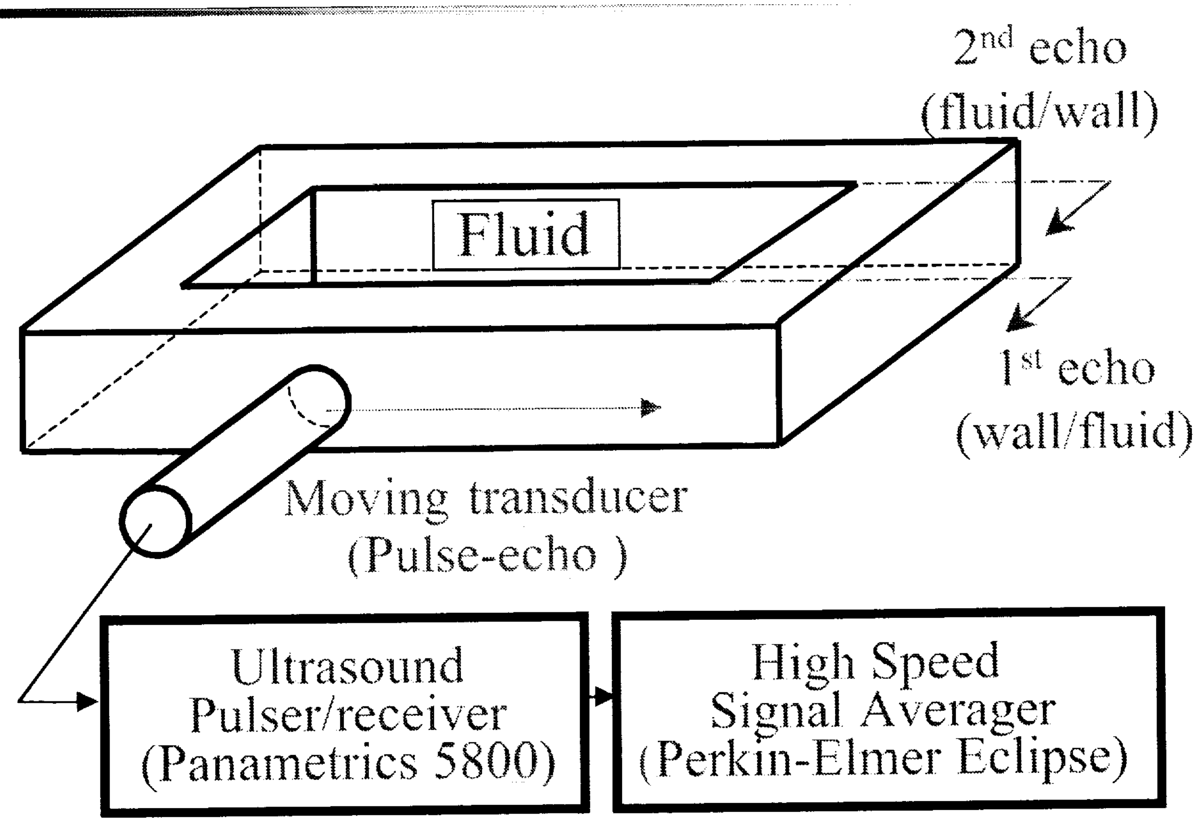


T: temperature

C: sound velocity

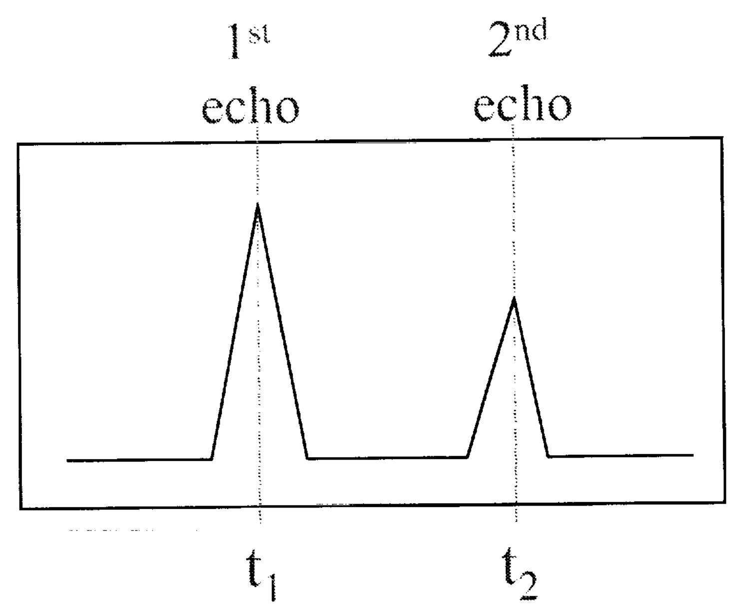
tof: time of flight

Experimental Procedure



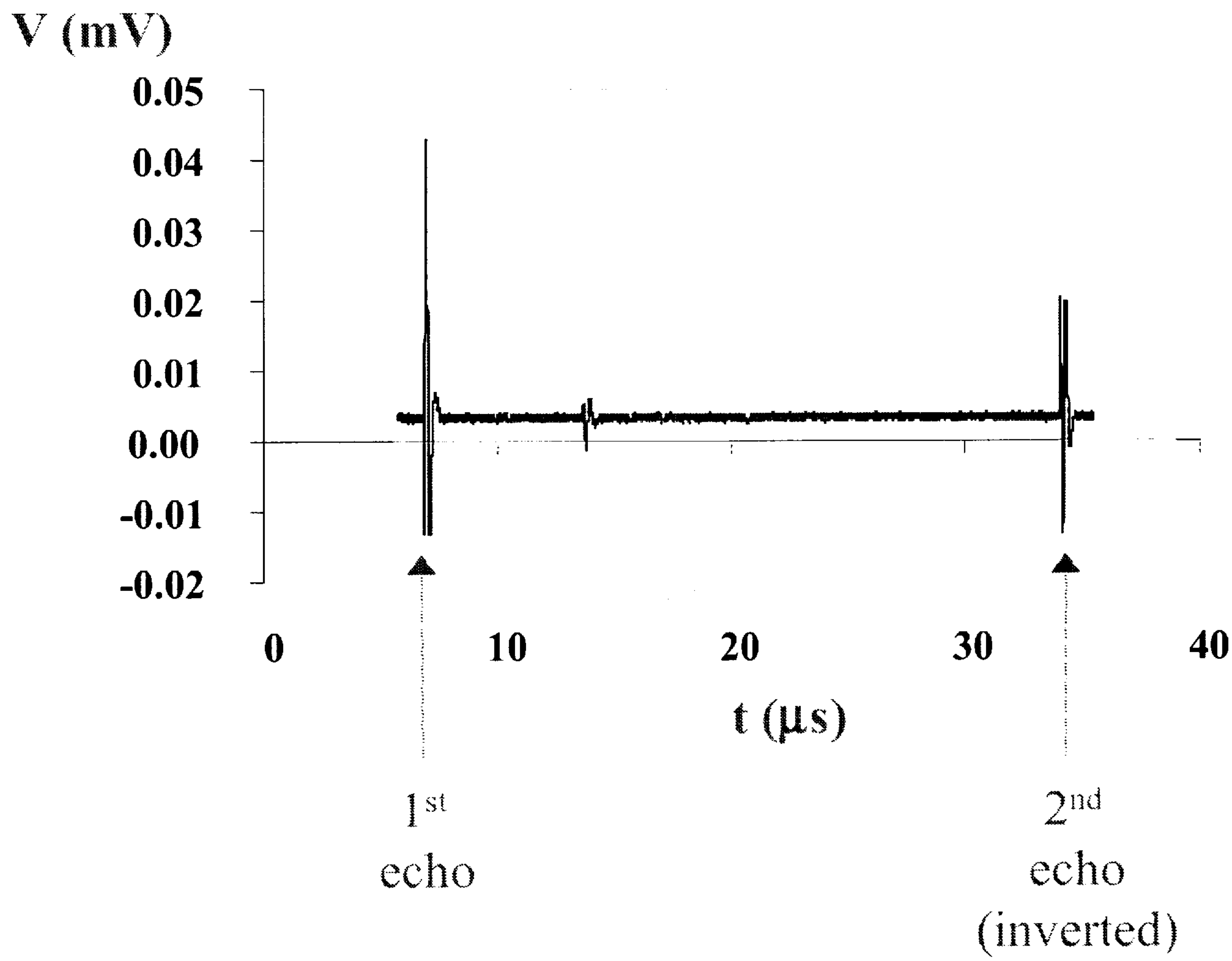
Schematic Ultrasound Signal

(For each location)



$$t_2 - t_1 = 2\text{tof (time of flight)}$$

Sample Signal



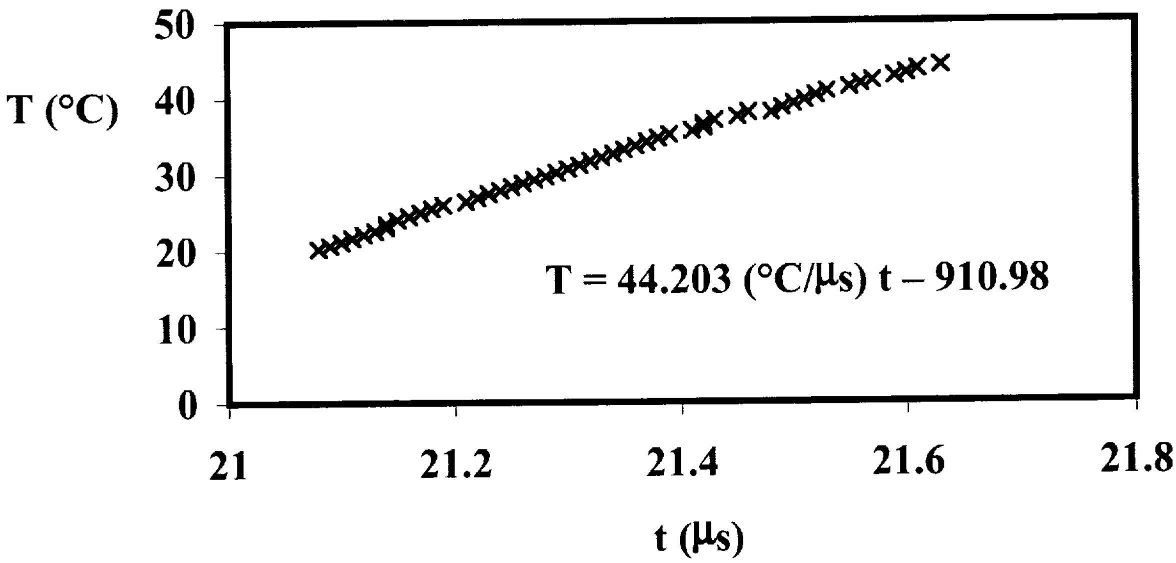
Transducer diameter = 0.35 Inch
Power in pulse = 25 µJ
Resonant frequency = 2.25 MHz
Pulse width = 0.6 µs
Pulse repetition rate = 1 kHz

Calibration for Glycerol

Temperature vs time of flight

Vertical $\Delta T = 0\ °C$

➔ no convection

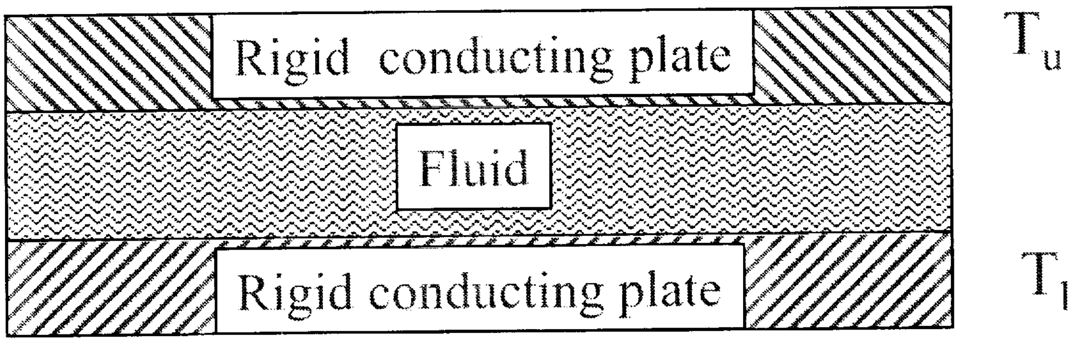


Glycerol : Prandtl Number Pr = 7613

T = temperature

t = 2tof (time of flight)

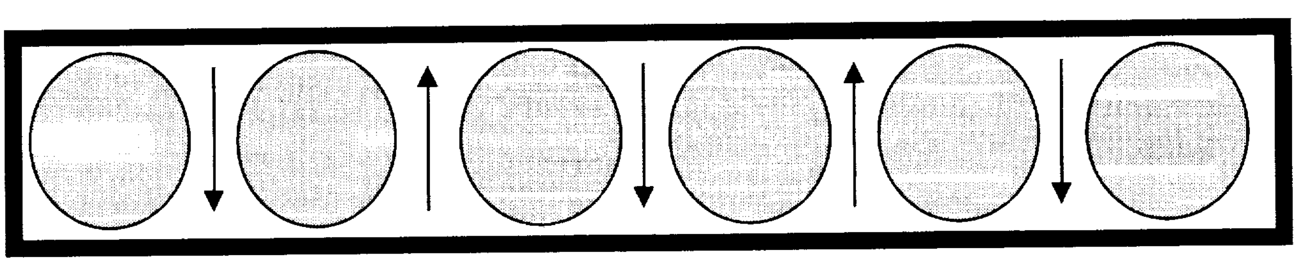
Rayleigh-Bénard configuration



$$\Delta T = T_l - T_u > \Delta T_c$$

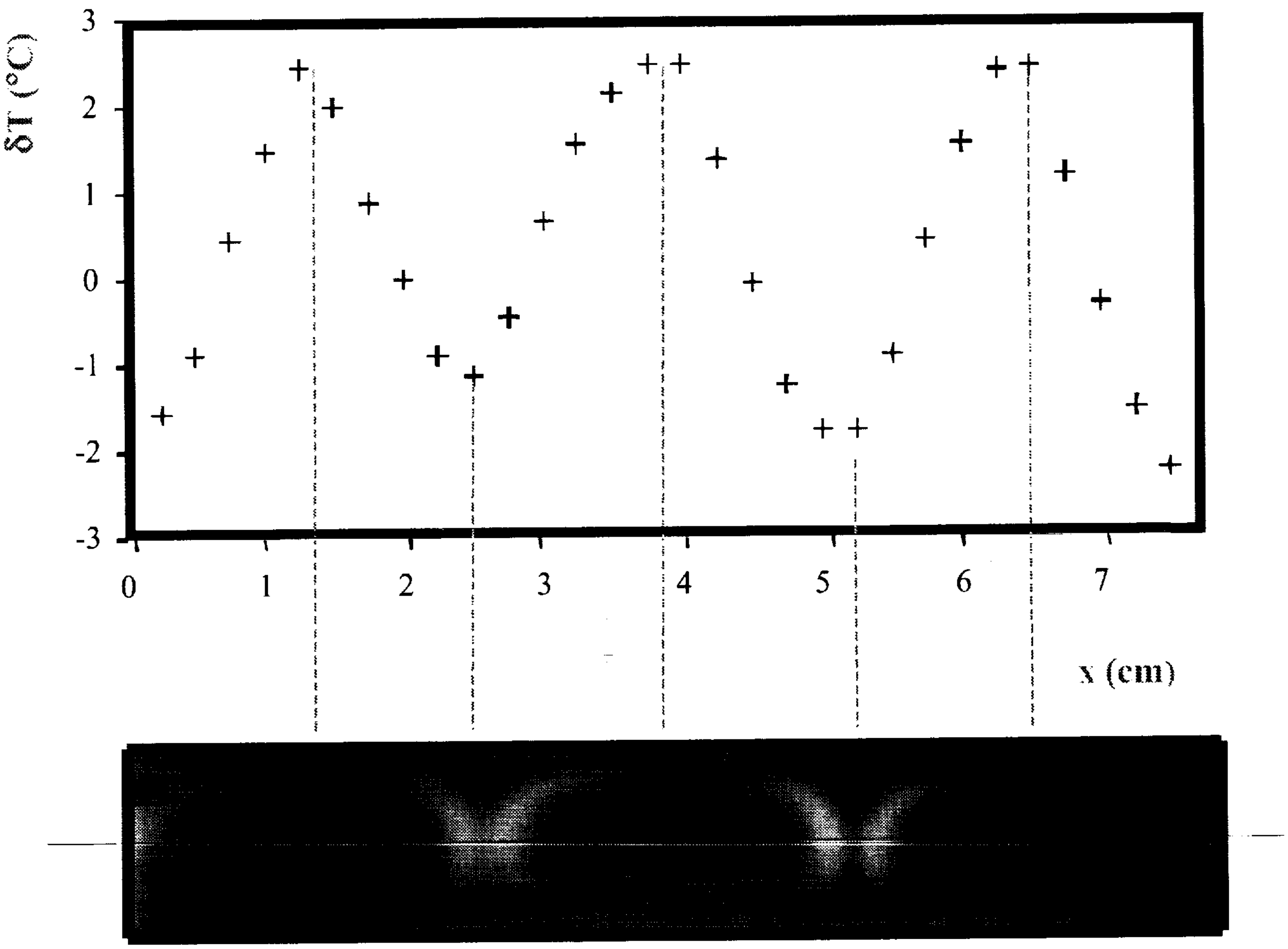
(ΔT_c = critical temperature difference for onset of convection)

Convection roll pattern (schematic)



Results with Glycerol

Ultrasound measurements



Thermochromic liquid crystals

(T = 29 °C: red start, T = 33 °C: blue start)

δT: deviation from the mean temperature

Cell dimensions: 7.77 cm long, 2.00 cm wide, 1.3 cm high

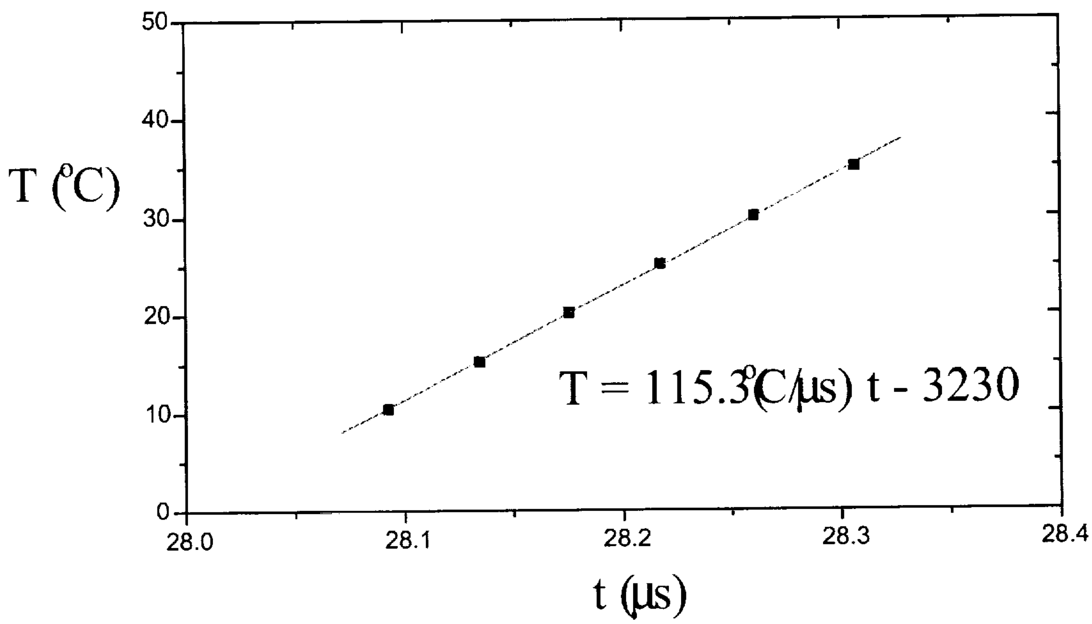
$\Delta T = 14\ °C \rightarrow$ Rayleigh Number $Ra = 1.2\ Ra_c$ (critical value)

Calibration of Mercury

Temperature vs time of flight

Vertical $\Delta T = 0\ ^{\circ}C$

➔no convection



Mercury: Prandtl number Pr = 0.027

T = temperature

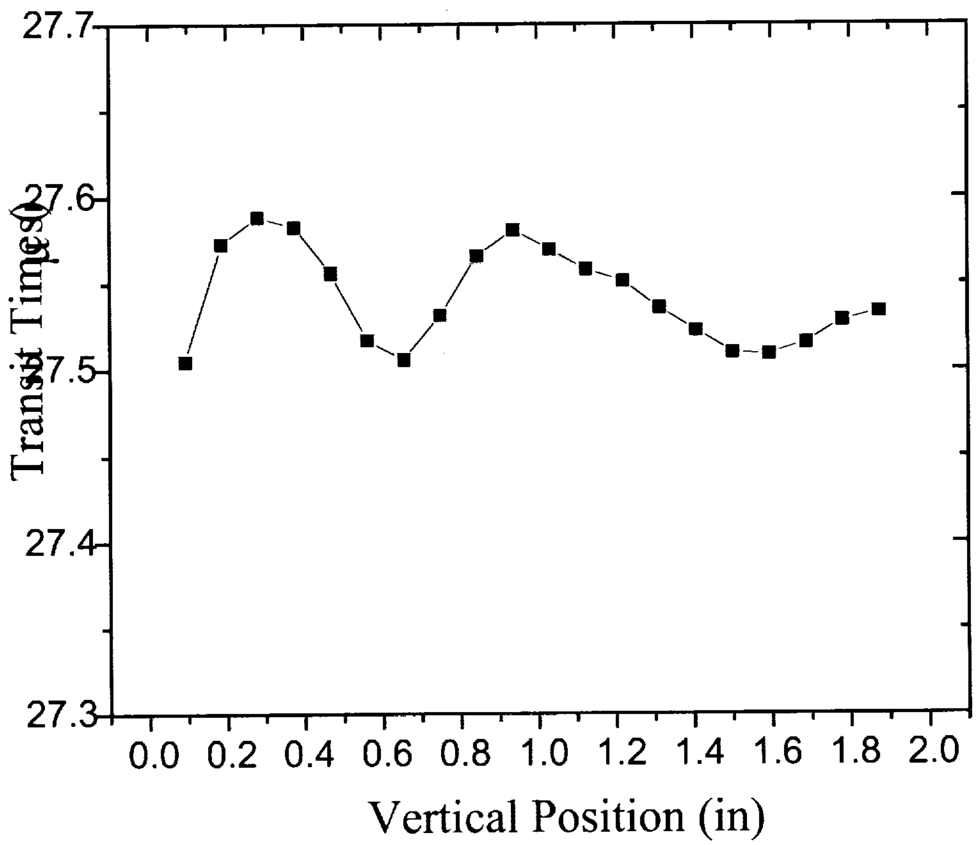
t = 2tof (time of flight)

Stainless Cell #1 Background

Cell dimensions: 4.00 cm long, 2.00 cm wide, 5.00 cm tall

T = 20.0 C, DT = 0

→ No convection



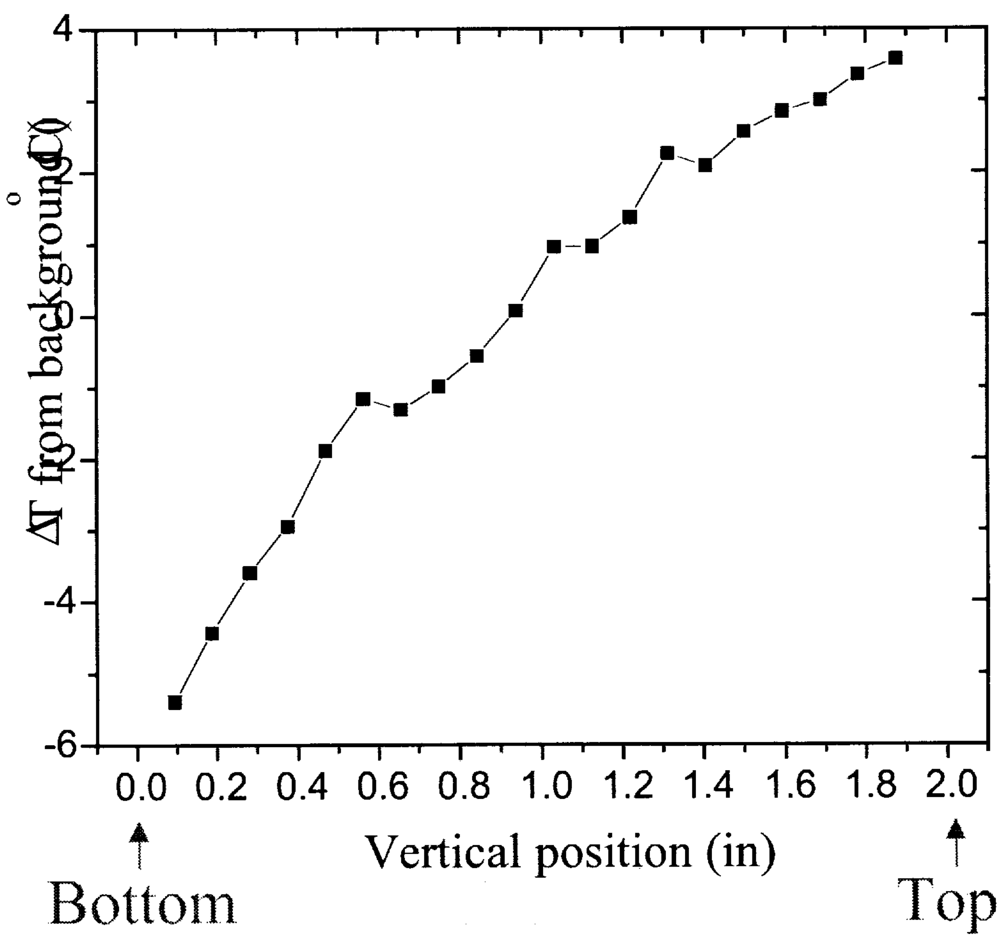
Nonuniform cell width due to precision of machining

Use these points for background compensation

Tall Cell--Inverted Gradient

Imposed inverted gradient ~15 C

→ No convection

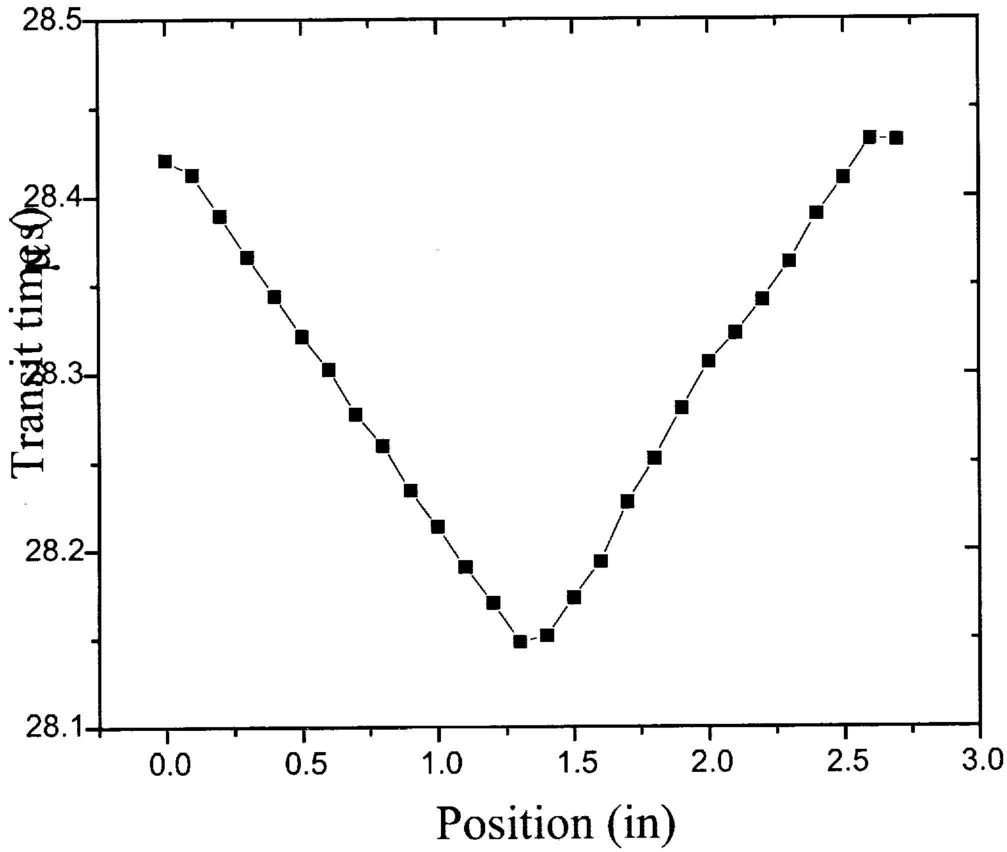


Stainless Cell #2 Background

Cell dimensions same as Plexiglas cell used with Glycerol

T = 20.0 C, DT = 0

=> No convection

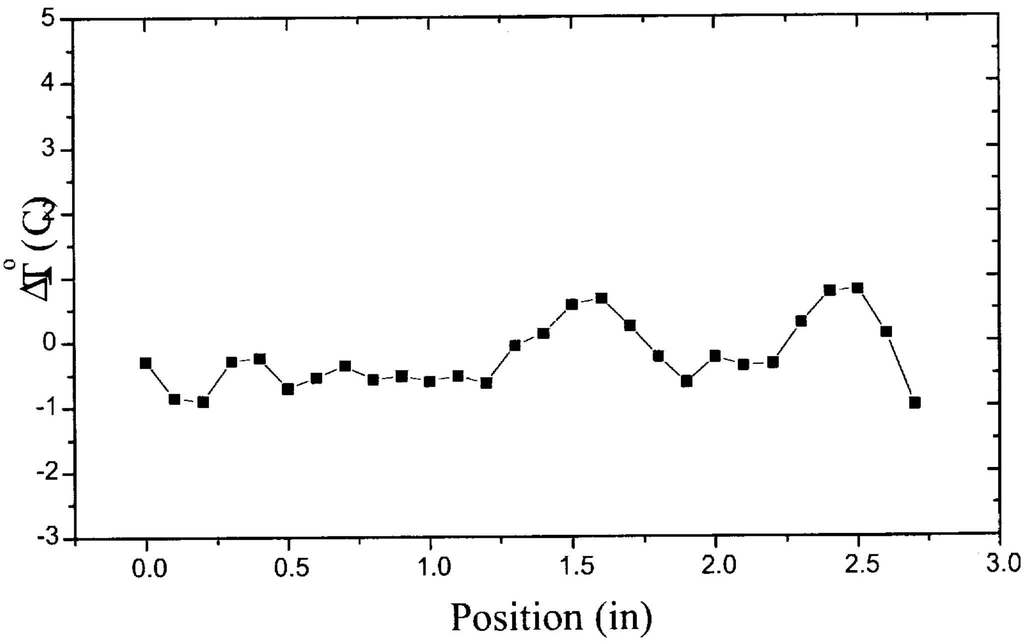


Nonuniform cell width due to precision of machining

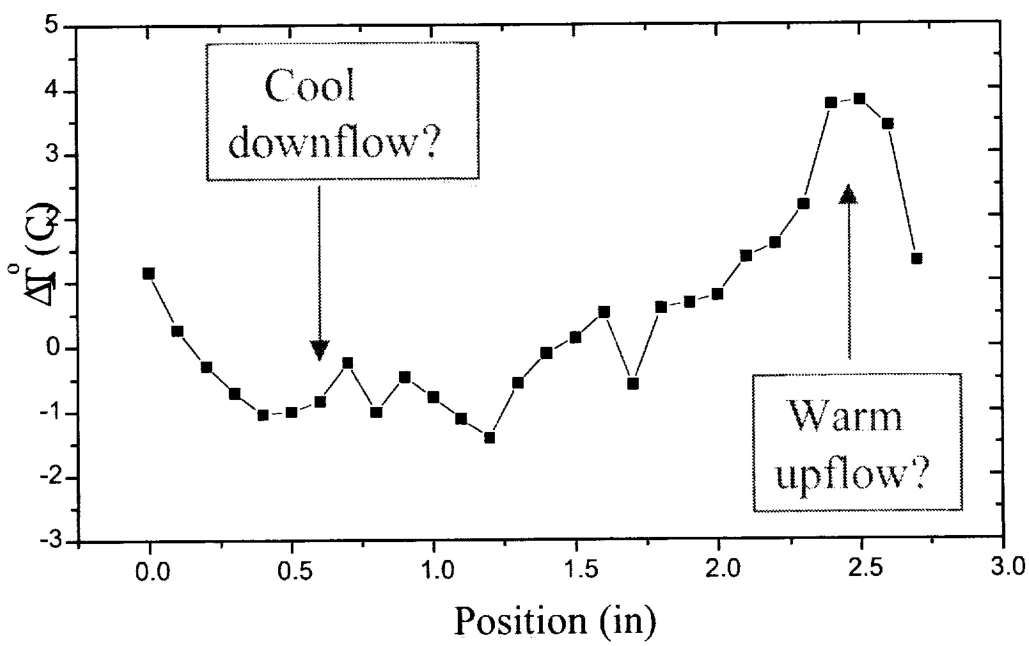
Use these points for background compensation

Mercury Convection

ΔT = 2.3 C



ΔT = 5.6 C



Conclusions

* Development of a new technique: measurement of thermal fields using ultrasound

* Application to a transparent fluid (Glycerol)

--Temperature resolution of ~ 0.1 °C

--Validation: pattern visualization with thermochromic liquid crystals

* Application to an opaque liquid (Mercury)

* Future ➔ Transient states using an array of transducers