Ultrasound Thermal Field Imaging of Opaque Fluids [1]

C. David Andereck
Department of Physics
The Ohio State University
174 W. 18th Ave.
Columbus, Ohio 43210
E-mail: andereck@mps.ohio-state.edu

Introduction

- 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 examples of pattern formation in non-equilibrium systems (Cross and Hohenberg (1993), Ahlers (1991), and Koschmieder (1993)).

- It is much more difficult to study the flows of opaque fluids such as liquid metals and certain semiconductors and polymer melts, owing to the lack of optical access to the interior of the fluid. The thermal properties of liquid metals are quite different from typically used transparent fluids, which means that an attempt to model with a transparent fluid the detailed flow properties of a liquid metal under thermal stress is doomed to failure (see Carpenter and Homsy (1989), who discuss the effect of the Prandtl number on surface tension gradients).

- Likewise, polymer melts and solutions, being viscoelastic materials, are also impossible to model with typical transparent Newtonian fluids. Nevertheless there are numerous situations in which it is important to understand the behavior of the flow of these fluids and therefore new diagnostic methods are needed.

- In this presentation we will briefly discuss optical techniques for transparent fluids, review the basic approaches that have been tried in opaque fluids, and then will discuss the use of ultrasound as a tool for measuring the thermal field, and *hence the flow pattern*, in opaque fluid flows. Such a tool will find its ultimate payoff in materials processing applications in microgravity where thermal gradients may be large although velocities may be very low.

Diagnostic Tools for Studying Flows of Transparent Fluids

- **Particle Seeding:**

  - **Isotropic particles:** By tracking small isotropic particles the 2D or 3D flow field can be mapped. This is the basis for particle image velocimetry (PIV) and particle tracking velocimetry (Guezennec, et al. (1994)). The necessary ingredient is a particle that is small compared with expected flow features and that is nearly neutrally buoyant. There is typically a large investment in software to analyze the data, but the outcome is a flow field map with only a minimum invasion of the fluid.

  - **Non-isotropic particles:** The particles used can be anything from aluminum powder to Kalliroscope (Matisse and Gorman (1984)), the latter being polymeric flakes that are

somewhat more dense than water, and of the order of a few microns in size. These particles attempt to align with the flow (Savas (1985)). Their reflectance depends on their orientation to the viewing direction, so the flow field is revealed by the presence of higher and lower levels of reflected light in different regions of the flow. They have proved useful for extracting qualitative, and some quantitative, information about flow patterns (Gorman and Swinney (1982), Shaw, et al. (1982), Hegseth, et al. (1996)).

- **Other Velocimetry Approaches:**

  - **Laser Doppler velocimetry (LDV)** (Somerscales (1981), Jacobs, et al. (1988)): The essence of the technique is that laser light is focused into a small volume of the fluid. As seed particles pass through this volume they scatter Doppler shifted light. This light is detected, and the resulting signal yields the velocity of the particle. Using the multiple wavelengths from an Ar laser it is possible to measure more than one velocity component at once. This system is capable of very high precision measurements of velocity, but requires scanning of the scattering volume to map the velocity field.

  - **Hot-wire probes** (Blackwelder (1981)): These probes rely on the flowing fluid to carry away thermal energy from a small wire of circular or planar cross section. Seeding of the flow is not needed and the technique works with opaque fluids, but the probes are quite invasive. Furthermore it is difficult to scan the flow field.

- **Thermal field imaging:**

  There are several non-invasive methods of visualizing the thermal field in a transparent fluid that take advantage of the variation of the optical index of refraction of the fluid with temperature. In each case the result is a map related to the average of the temperature field along the line of observation. This is particularly effective if the flow field is essentially 2D, however, the averaging may be useful in other, 3D, flows as well.

  - **Optical interferometry** (Goldstein (1983): This is an extremely sensitive technique. In a typical situation, a test chamber is placed in one of the two arms of a Mach-Zehnder interferometer. If the fluid temperature is uniform there will be a uniform phase shift of the light across the wavefront as it passes through the fluid. In the presence of temperature (index of refraction) variations there will be differing phase shifts across the chamber. When the light recombines with the light from the other arm unequal phase shifts result in a distortion of the fringe pattern (Prakash and Koster (1996)).

  - **Schlieren and shadowgraph** (Goldstein (1983)): These techniques rely on refraction of the light passing through the cell. Variation of the temperature in a plane perpendicular to the direction of light propagation results in regions in which the light emerging from the cell is either diverging or converging. This effect can be used to produce an image of the flow that reveals the pattern of rolls or cells in the flow. Contrast in a Schlieren (shadowgraph) image is proportional to the integral along the optical path through the test cell of the *first derivative (second derivative)* of the index of refraction in the direction perpendicular to the direction of propagation. Attempts to extract quantitative

information about the temperature field and nonlinear modes have been made (Dong and Ebadian (1992), Schöpf, Patterson and Brooker (1996), Kolodner and Williams (1990), Winkler and Kolodner (1992)). This approach has been used for many experiments in pattern formation in both liquids and gasses (Wu, et al. (1995)).

Diagnostic Tools for Studying Flows of Opaque Fluids

● **Velocimeters:**

  ● **Invasive probes:** Hot-wire probes may be used, as already described above. A second approach is to use an incorporated magnet probe, which works only in conducting fluids such as liquid metals (Hung and Andereck (1988)). In this system a small high-field magnet is placed at the surface of the fluid or just inside. On either side of the magnet are placed small electrodes. As the fluid flows through the magnetic field the conduction electrons move perpendicular to the flow in response to the Lorentz force, giving rise to a potential difference between the electrodes. The potential difference depends on the field strength and fluid properties, but the probe can be quite sensitive; we have used such a probe to measure velocities as small as 0.1 cm/s. This type of probe, though very sensitive, suffers from being invasive and difficult to scan.

  ● **Ultrasound Doppler velocimetry:** This technique has been used in both transparent and opaque fluids (Takeda (1986) and (1991)). The fluid is seeded with small particles that serve as scattering sites for ultrasound pulses introduced from a transducer in contact with the fluid. As the pulse propagates sound is scattered from the seed particles, and is Doppler shifted. When the scattered sound is received two measurements are made: The first is the time the signal was received, and the second is the shift of the ultrasound signal frequency. From the former the electronics extracts the distance of the scatterer from the transducer/detector. From the latter the velocity of the scatterer, and hence of the fluid, is determined. The result is a map of one component of the velocity field along the line of sight. This is an improvement over LDV, which provides only a velocity at one point at a time, and it is also usable in opaque fluids such as mercury (Takeda (1987)). Of course, a difficulty is finding appropriate seed particles, an important consideration for liquid metals. A second drawback is that the velocity resolution is not as high as for LDV, the lowest detectable velocity being a few cm/s. This places severe limits on its usefulness in weak flows such as might be found near convective onset.

● **Temperature probes:**

  ● **Thermistors and thermocouples:** These probes offer very high precision at a point, but suffer from invasive characteristics. It is possible to embed several probes in the test cell walls to obtain a crude map of the field at the boundary, or to detect fluctuations in temperature (Busse and Sommermann (1996)). It is more problematic to measure temperatures in the interior of the fluid. The thermistor also introduces a small amount of heating. One is faced with either constructing a grid of a very large number of these probes to obtain enough spatial resolution (Pfeffer, Buzyna and Kung (1980)), or providing a traversing system for the probe so that different points may be reached (Hung

and Andereck (1988)). Neither approach is particularly satisfactory.

- **X-ray imaging**: It is possible to use x-rays in a manner similar to the use of visible light in the optical techniques described previously. Signal attenuation variations due to sample density discontinuities is the basis for medical imaging and non-destructive testing of solids. This approach is now being used for imaging density variations in solidification (Campbell and Koster (1994), Pool and Koster (1994), Campbell and Koster (1995a) and (1995b), Derebail and Koster (1997), and Koster, Derebail and Groetzbach (1997)) This has proven quite successful in a limited range of operating conditions. The drawbacks are not trivial. Obviously there is a safety aspect to it. This is not an insurmountable problem, although it is an inconvenience. To achieve energetic x-rays requires considerable power input, possibly a problem in space-based experiments. More importantly there are limitations on the depth of the fluid that may be probed, at least for liquid metals: The penetration depth for x-rays is a fraction of a cm for energies up to 1 Mev for mercury. As a result, the experiments referenced above were for test cells of only 2 mm thickness. At higher energies one might also expect considerable sample heating to occur as well. Although in principle x-rays might be useful diagnostics for certain situations involving opaque fluids, in practice there are severe limitations.

Proposed Investigations

- **Introduction:** The imaging of velocity and thermal fields in opaque fluids is in a very unsatisfactory state. Current techniques require invasive probes or seed particles or only yield the temperature or velocity at a point in the flow. There are no elegant approaches for liquid metals in particular, even though a knowledge of the velocity and temperature fields in such fluids is of great importance for materials processing. *We propose the use of ultrasound imaging of the thermal field as a partial solution to this problem.* Why use ultrasound? It is non-invasive and no seeding is required. Just as the index of refraction for light varies with the temperature of the material, so sound speed varies with the temperature of the medium through which the sound propagates. So ultrasound may be used in a way analogous to the non-invasive optical techniques, even with fluids that are opaque to visible light. Spatial resolution of a few millimeters or less is achievable with moderate frequencies (the wavelength is 0.015 cm at 10 MHz). Temperature resolution of a fraction of a degree is possible. Sensor arrays allow for rapid scanning of entire cross-sections of a test cell with no moving parts, a dramatic improvement over single point temperature measurements. Ultrasound thermal field imaging offers a very significant improvement potential over current techniques, while not being technologically beyond the state-of-the-art (see Shung and Zipparo (1996).

- **Proof of concept:** To begin we propose an ultrasound analog of optical interferometry, but *since we know precisely the phase of the emitted pulse there is no need for a reference beam.* Suppose there is a variation in the temperature of the fluid across the test cell. If a pulse of ultrasound traverses the fluid along a line at temperature T_1 it will take a time determined by both the distance across the chamber and the speed of sound at that temperature. If in some other region of the system the temperature is $T_2 \neq T_1$, then the traversal time will be different owing to the sound velocity difference. By moving the transducers along the chamber we will map out the sound speed as a function of

position, and thereby indirectly measure the fluid temperature field. We will begin with a simple rectangular cell with transparent sidewalls, probably containing water as the convecting fluid, and with an externally imposed vertical temperature gradient. This allows both optical shadowgraph and ultrasound imaging for confirmation that the ultrasound imaging is faithful to the pattern. Molten gallium would be a particularly interesting first opaque fluid to study in view of its relation to semiconductor processing. Braunsfurth and Mullin (1996) studied molten gallium in a long, square cross section chamber, with an imposed horizontal temperature difference along the channel, a model version of the Bridgman system. Their probe was a set of two thermocouples just slightly below the surface. They found numerous interesting oscillatory states, but the only characterization was in terms of time dependence at one or two points. Lacking was an indication of the spatial nature of the flow. Both spatial and temporal information is needed to model these flows, a possibility with the proposed system.

- **Further instrumentation development**: A more sophisticated approach would involve an array of transmitters and detectors, eliminating the traversing of the probe, but the principle is the same. Also, with a large rectangular transmitter and an array of receivers an analog to the shadowgraph technique could be constructed. The temperature variations across the fluid would lead to focusing and defocusing of the sound pulses, and simple intensity measurements would yield a picture of the flow pattern.

- **Future Directions:** The future possibilities for this diagnostic tool are varied. One important direction would be to study the thermal field of a liquid metal in contact with another liquid, so that thermocapillary effects at the interface would be important (Géoris, et al.(1993), Géoris, P. and Legros, J. C. (1993) and (1996), Prakash and Koster (1993), (1994a) and (1994b)). It will be possible to investigate solidification of pure metals and binary alloys. One can imagine extending the technique to tomography by using phased arrays of transducers. Imaging the thermal field of polymer melts would be of interest to the materials processing community. Another exciting possibility is the study of magnetohydrodynamic (MHD) systems. The influence of magnetic fields on convective liquid metals is of interest in solidification, and the general MHD problem shows up in a variety of contexts (Takeshita et al. (1996), Segawa et al. (1996)). The ability to observe the patterns deep in the interior of such flows would be very valuable.

Bibliography

Ahlers, G., *Physica D* **51**, 421 (1991).

Blackwelder, R. F., in *Methods of Experimental Physics: Volume 18, Fluid Dynamics, Part A*, R. J. Emrich, ed. (Academic, New York, 1981), p.259.

Braunsfurth, M. G. and Mullin, T., *J. Fluid Mech.* **327, 199** (1996).

Busse, F. H., and Sommermann, G., in *Advances in Multi-Fluid Flows*, eds. Y.Y. Renardy, A.V. Coward, D.T. Papageorgiou, S.-M. Sun (SIAM, Philadelphia, 1996), p. 33

Campbell, T. A., and Koster, J. N., *J. Crystal Growth* **140**, 414 (1994).

Campbell, T. A., and Koster, J. N., *J. Crystal Growth* **147**, 408 (1995a).

Campbell, T. A., and Koster, J. N., *Meas. Sci. Tech.* **6**, 472 (1995).

Carpenter, B. M., and Homsy, G. M., *J. Fluid Mech.* **207**, 121 (1989).

Cross, M. C., and Hohenberg, P. C., *Rev. Mod. Phys.* **65**,   851 (1993).

Derebail, R., and Koster, J. N., *Int. J. Heat Mass Transfer* **40**, 1169 (1997).

Dong, Z. F., and Ebadian, M. A., *Int. J. Heat Mass Transfer* **35**, 1833 (1992).

Géoris, P., Hennenberg, M., Simanovskii, I. B., Nepomniaschy, A. , Wertgeim, I. I., Legros, J. C., *Phys Fluids A* **5**, 1575 (1993).

Géoris, P. and Legros, J. C., in Proceedings of the 44th Congress of the International Astronautical Federation, Oct 16-22, 1993, Graz, Austria.

Géoris, P. and Legros, J. C., in *Materials and Fluids Under Low Gravity*, L. Ratke, H. Walter, B. Feuerbacher, Eds. (Springer, Berlin, 1996), p. 299.

Goldstein, R. J. *Fluid Mechanics Measurements* (Hemisphere, Springer, Washington, 1983).

Gorman, M. A., and Swinney, H. L., *J. Fluid Mech.* **117**, 123 (1982).

Guezennec, Y. G., Brodkey, R. S., Trigui, N., and Kent, J. C., *Exp. Fluids* **17**, 209 (1994).

Hegseth, J. J., Baxter, G. W., and Andereck, C. D., *Phys. Rev. E* **53**, 507 (1996).

Hung, M-C., and Andereck, C. D., *Phys. Lett. A* **132**, 253 (1988).

Jacobs, D. A., Jacobs, C. W., and Andereck, C. D., *Phys. Fluids* **31**, 3457 (1988).

Kolodner, P., and Williams, H., in *Proceedings of the NATO Advanced Research Workshop on Nonlinear Evolution of Spatio-Temporal Structures in Dissipative Continuous Systems*, F. H. Busse and L. Kramer, eds. (Plenum, New York, 1990), p. 73.

Koschmieder, E. L. *Bénard Cells and Taylor Vortices* (Cambridge, New York, 1993).

Koster, J. N., Derebail, R., and Groetzbach, A., *Appl. Phys. A* **64**, 45 (1997).

Matisse, P. and Gorman, M., *Phys. Fluids*, **27**, 759 (1984).

Pfeffer, R. L., Buzyna, G., and Kung, R., *J. Atmos. Sci.* **37**, 2129 (1980).

Pool, R. E., and Koster, J. N., *Int. J. Heat Mass Transfer* **37**, 2583 (1994).

Prakash, A., and Koster, J. N., *Int. J. Multiphase Flow* **20**, 383 (1994a).

Prakash, A., and Koster, J. N., *Int. J. Multiphase Flow* **20**, 397 (1994b).

Prakash, A., and Koster, J. N., *Eur. J. Mech. B/Fluids* **12**, 635 1993).

Prakash, A., and Koster, J. N., *Trans. ASME* **118**, 366 (1996).

Savas, O., *J. Fluid Mech.* **152**, 235 (1985).

Schöpf, W., Patterson, J. C., and Brooker, A. M. H., *Exp. Fluids* **21**, 331 (1996).

Segawa, T., Sano, M., Naest, A., and Glazier, J. A., preprint (1996).

Shaw, R. S., Andereck, C. D., Reith, L. A., and Swinney, H. L., *Phys. Rev. Lett.* **48**, 1172 (1982).

Shung, K. K., and Zipparo, M., *IEEE Eng. in Medicine and Biol.* **15**, 20 (1996).

Somerscales, E. F. C., in *Methods of Experimental Physics: Volume 18, Fluid Dynamics, Part A*, R. J. Emrich, ed. (Academic, New York, 1981), p. 93.

Takeda, Y., *Int. J. Heat Fluid Flow* **7**, 313 (1986).

Takeda, Y., *Nucl. Tech.* **79**, (1987).

Takeda, Y., *Nucl. Eng. and Design* **126**, 277 (1991).

Takeshita, T., Segawa, T., Glazier, J. A., and Sano, M., *Phys. Rev. Lett.* **76**, 1465 (1996).

Winkler, B. L., and Kolodner, P., *J. Fluid Mech.* **240**, 31 (1992).

Wu, M., Ahlers, G., and Cannell, D. C., *Phys. Rev. Lett.* **75**, 1743(1995).