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THERMOCAPILLARY CONVECTION IN FLOATING ZONES UNDER SIMULATED REDUCED-GRAVITY CONDITIONS

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ABSTRACT

The present study demonstrated that calculated thermocapillary convection in a non-cylindrical floating zone can now be compared with measured one, by considering the lens effect of the floating zone. Flow visualization and computer simulation of thermocapillary convection in a silicone oil zone and a molten zone in an $NaNO_3$ rod were conducted. The calculated results agree very well with the measured ones, including the free surface shapes, the solid/melt interface shapes and the velocity fields.

INTRODUCTION

Thermocapillary convection becomes significantly more important as gravity and hence gravity-induced natural convection are reduced. Flow visualization has been widely used to study thermocapillary convection in floating zones. In ground-based experiments simulating the reduced-gravity condition the floating zones, though dominated by thermocapillary convection, are often non-cylindrical in shape. In flight experiments the floating zones have to be non-cylindrical in shape, if the significant effect of the free-surface shape on thermocapillary convection is to be studied. The optical distortions due to the lens effect of these non-cylindrical floating zones prevent the visualized results from being used to verify the calculated ones or from being interpreted properly. Recently, equations have been derived to quantitatively describe such a lens effect [1]. The objective of the present study is to demonstrate that measured and calculated velocity fields can now be compared quantitatively by considering the lens effect.

In the present study flow visualization and computer simulation are conducted in a silicone oil zone and a molten zone of $NaNO_3$. The calculated and measured results are compared to each other.

FLOW VISUALIZATION

A 5-centistoke silicone oil zone about 0.3 cm long was established between two 0.4 cm diameter Cu rods, the upper and lower rods being held constant at 37.9 and 27.9°C, respectively. A small zone length and diameter help insure that thermocapillary convection dominates over natural convection in ground-based experiments as in flight experiments.

A laser light-cut technique and fine aluminum tracer particles were used to reveal the flow pattern. A beam chopper, a high contrast film and a macrophoto system were used for photographing. The developed negative film was projected onto a large graph paper screen of 1 mm grid spacing, the floating zone covering an area of about 20 cm by 30 cm. The locations of the particle images were used to construct the velocity fields.

A molten zone was produced in a 0.4 cm diameter $NaNO_3$ rod in a vacuum chamber with the help of a Pt ring heater. The same light-cut technique was used for flow visualization.

In both cases, thermocapillary convection was steady and axisymmetric. No flow oscillation was observed.

COMPUTER SIMULATION

Convection in the floating zone is assumed to be at the steady state, laminar and axisymmetric. The governing equations, boundary conditions and method of solution are similar to those described elsewhere [2,3]. In brief, a control-volume finite difference method was used, with body-fitted general (non-orthogonal) curvilinear coördinates having variable grid spacing. The free surface is calculated based on the normal stress balance. The physical properties have been given elsewhere [2,3].

RESULTS AND DISCUSSION

In order to show what the flow pattern looks like, results from a similar oil zone reported in the previous year [3] are shown in Fig. 1. This comparison between the calculated and converted flow pattern (LHS) and the observed one (RHS) is believed to be the first one for a non-cylindrical zone.

The measured velocity field in the present silicone oil zone is shown on the LHS of Fig. 2a. It is interpolated and shown on the RHS of the same figure, only on some (not all) grid points in order to be legible.

As shown in Fig. 3a, the calculated free surface shape agrees very well with the observed one. The grid mesh is shown on the LHS of Fig. 3b. The calculated velocity field is shown on the LHS of Fig. 2b on selected grid points. It is then converted, by considering the lens effect of the floating zone (refractive index $n = 1.396$), and shown on the RHS of the same figure. Due to the significant lens effect this conversion causes several layers of velocity vectors near the free surface to fuse together into a thin dark strip (deleted for clarity) along the free surface.

Figure 4 shows the calculated and measured velocity distributions along the grid lines shown on the RHS of Fig. 3b. As shown, the agreement is very good.

Similar results are shown in Figs. 5 and 6 for the $NaNO_3$ molten zone. As shown, the agreement between the calculated and measured results is very good. Since the melt is about 10 pct lighter than the solid, the melt diameter is on the average larger than the solid diameter. Near the top of grid line (f), however, the calculated solid/melt interface appears somewhat higher than the observed one, thus causing the calculated local axial velocity to deviate significantly from the measured one. More detailed discussion will be given elsewhere [4].

FUTURE PLANS

An image analysis system, consisting of a PC, a frame grabber, a CCD camera and a particle tracking software, will be set up to automatically generate the measured velocity fields.

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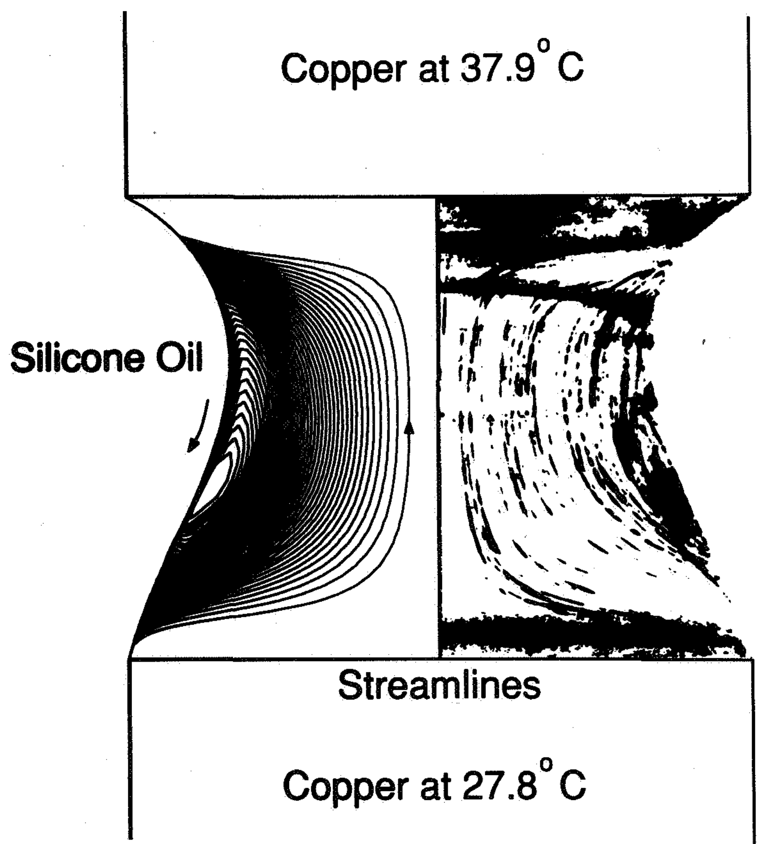


Fig. 1 Calculated and converted streamlines (LHS) and observed flow pattern (RHS) in a silicone oil zone[3].

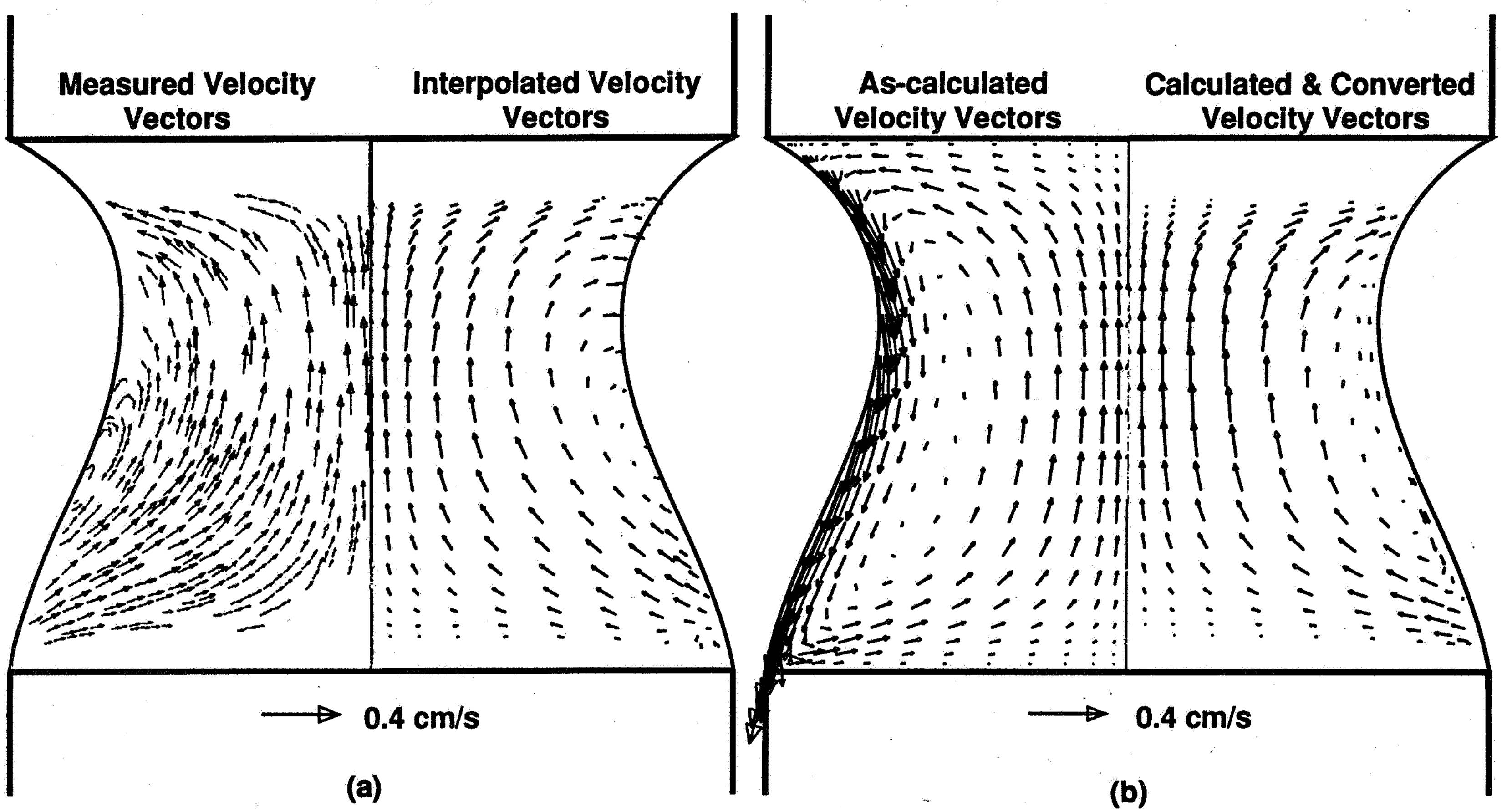
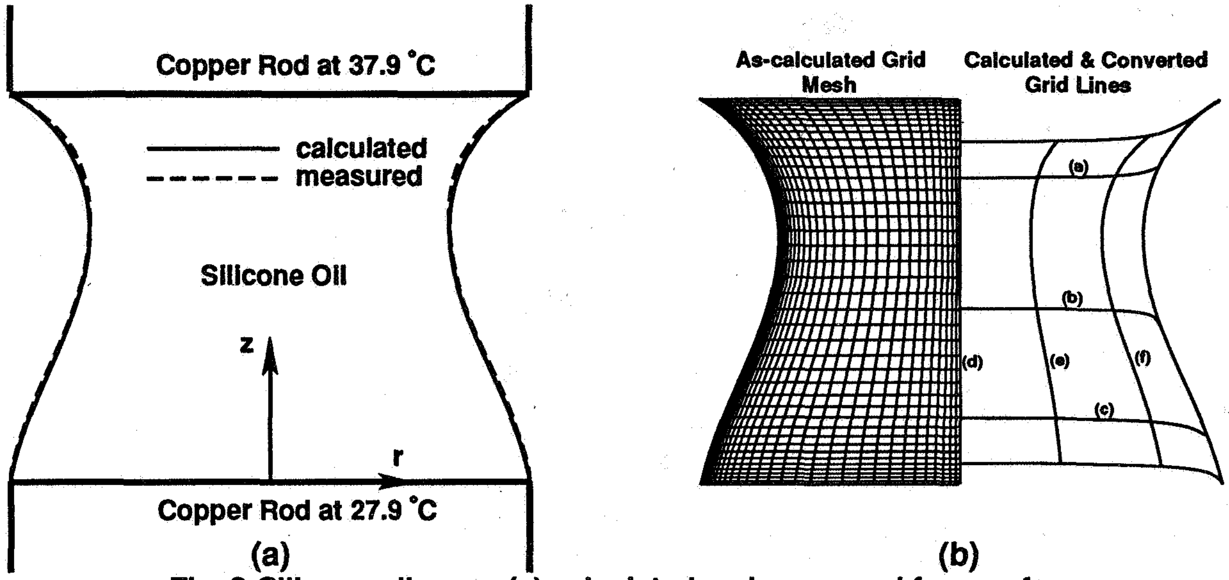
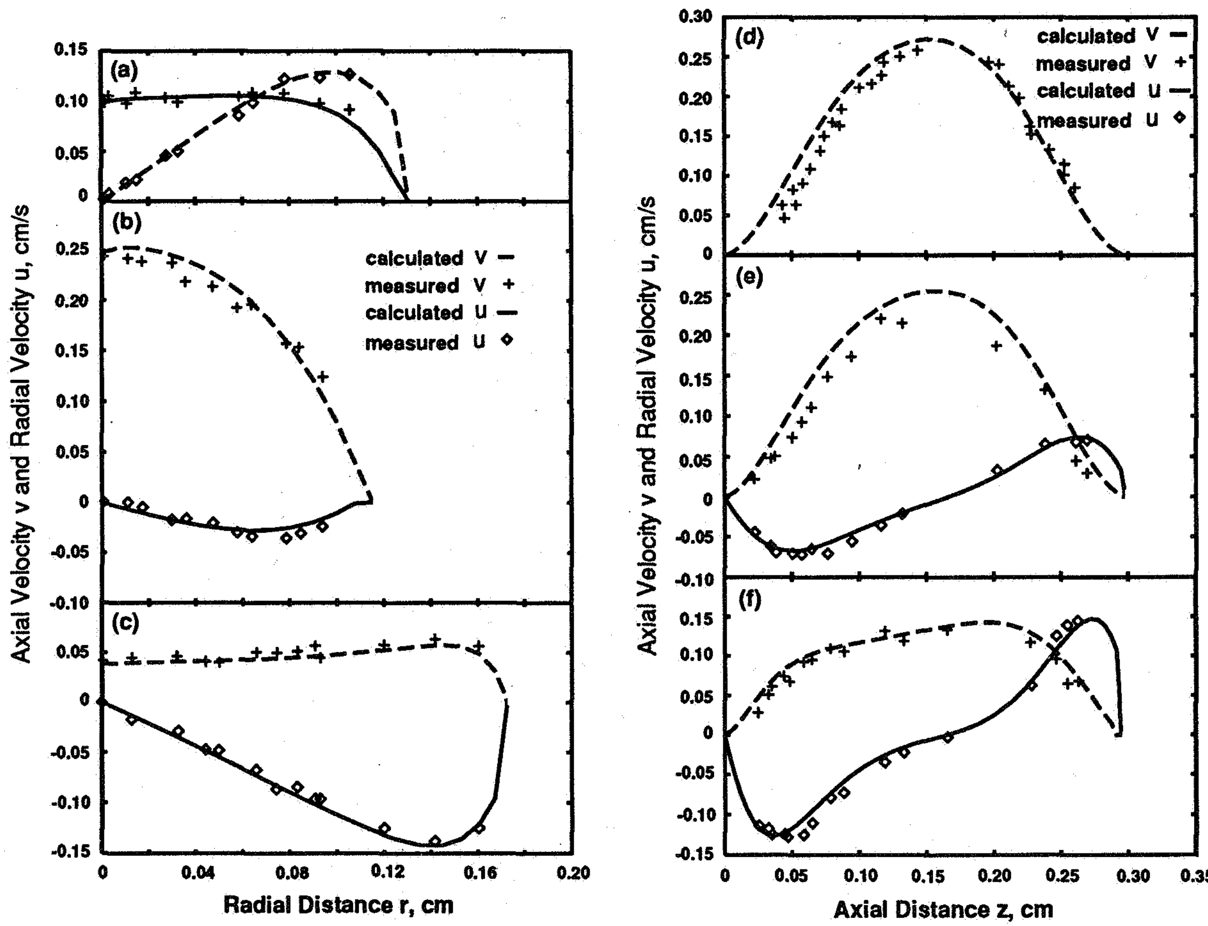


Fig. 2 Velocity vectors in silicone oil zone; (a) measured; (b) calculated



(a) (b)

Fig. 3 Silicone oil zone: (a) calculated and measured free surfaces; (b) grid mesh and lines.



(a) (b)

Fig. 4 Comparison between calculated and measured velocity vectors: (a) along lines (a), (b) and (c) in Fig. 2; (b) along lines (d), (e) and(f).

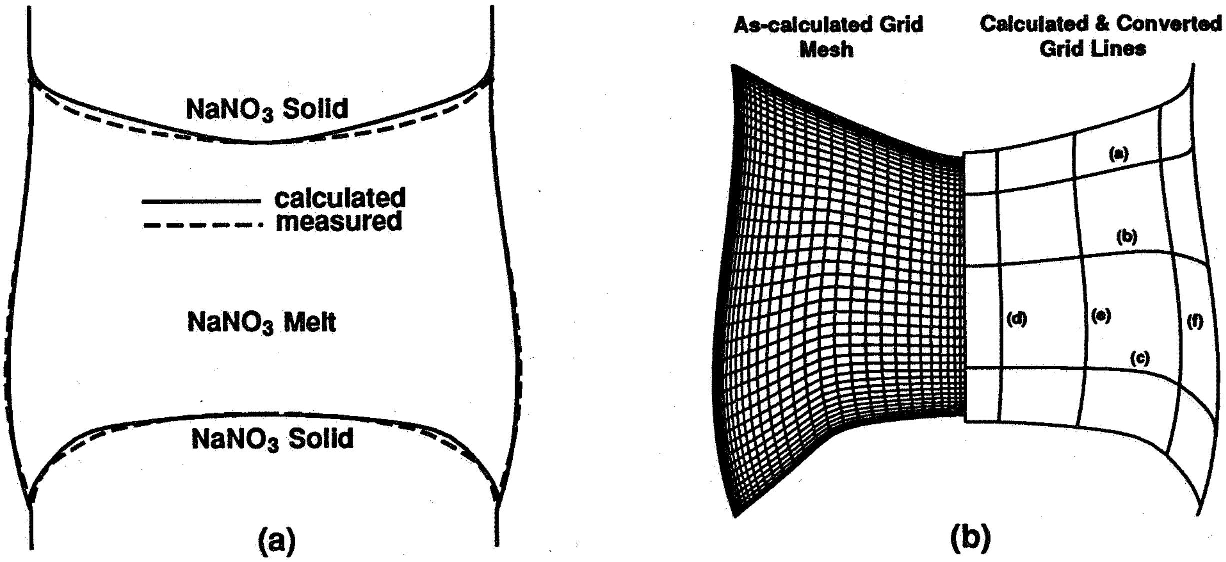


Fig. 5 NaNO$_3$ molten zone: (a) calculated and measured free surfaces; (b) grid mesh and lines.

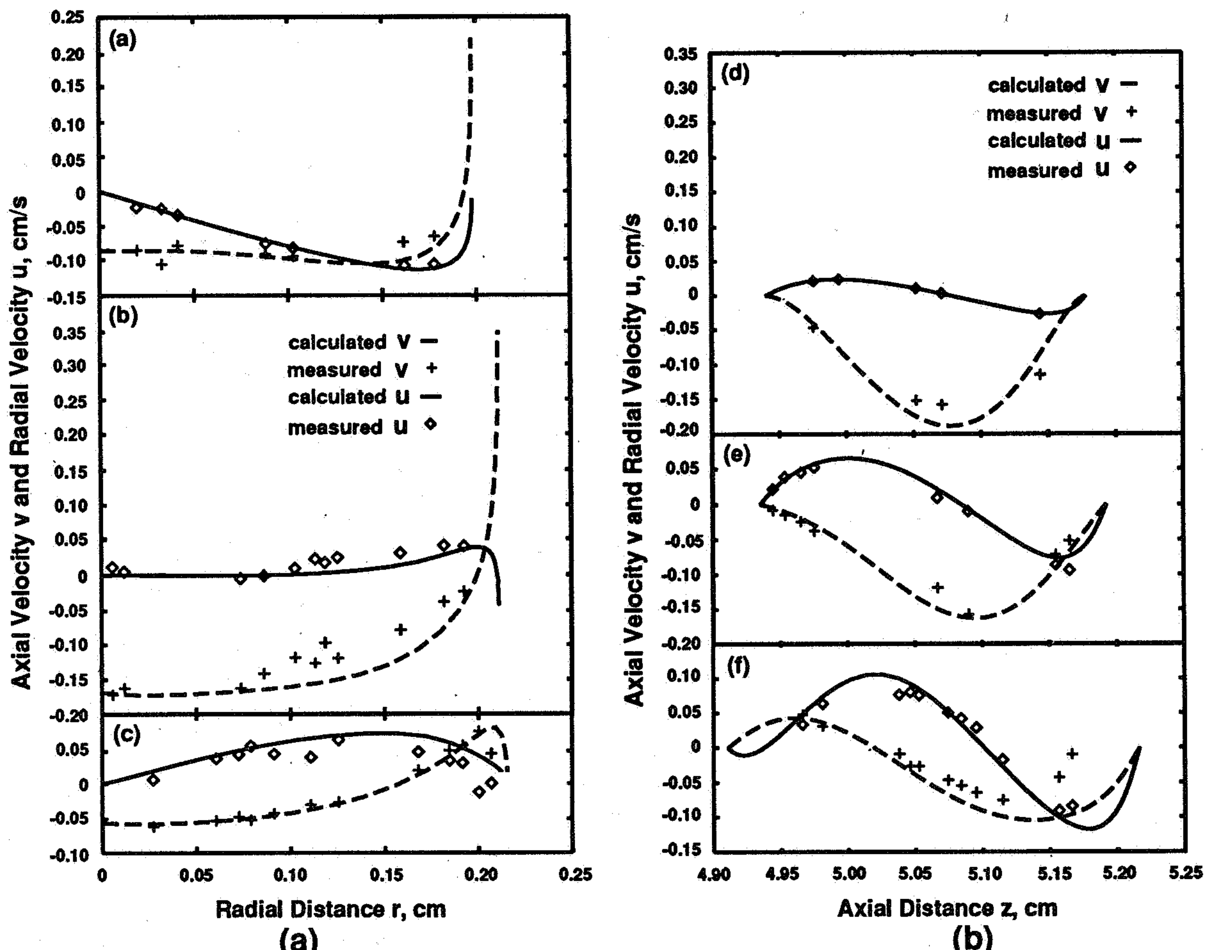


Fig. 6 Comparison between calculated and measured velocity vectors: (a) along lines (a), (b) and (c) in Fig. 4; (b) along lines (d), (e) and (f).