THERMOCAPILLARY CONVECTION IN A LOW Pr MATERIAL UNDER SIMULATED REDUCED-GRAVITY CONDITIONS

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ABSTRACT

A liquid bridge of tin was held between two vertical coaxial iron rods 4.5 mm in diameter and 4.6 mm apart. The temperatures at the top and bottom of the liquid bridge were 325 and 240°C, respectively. Flow oscillation was detected by a thermocouple in the liquid bridge. The amplitude and frequency of oscillation were around 1.3 °C and 5 Hz, respectively.

INTRODUCTION

The surface tension γ of a fluid is a function of temperature T and the temperature coefficient of the surface tension $\partial\gamma/\partial T$ is negative for most pure materials, e.g., -0.28 dyne cm^{-1} °C for silicon(1). Thermocapillary convection in a fluid is induced by the gradients of temperature and hence surface tension along the free surface of the fluid. It becomes significantly more important as gravity and hence gravity-induced buoyancy convection are reduced. It is often studied in the configuration of a liquid bridge, as shown in Fig. 1. A liquid bridge is sometimes called a half zone.

Numerous experiments have been conducted to study thermocapillary convection in high Pr materials, typically silicone oils. This is because these materials are transparent for convection to be observed and because they are easy to handle. Low Pr materials such as metals and semiconductors, on the other hand, are opaque and much more difficult to handle though they are also much more useful.

In the materials processing of low Pr materials, e.g., crystal growth and welding, thermocapillary convection can often play a significant role. In μg floating-zone crystal growth of silicon, for example, thermocapillary convection dominates in the molten zone. In fact, thermocapillary convection can be so strong as to become oscillatory, causing formation of dopant striations. Dopant striations are fluctuations in the dopant concentration and they cause the physical properties to vary in the crystal, thus degrading the crystal quality. They are caused by the growth rate fluctuations induced by flow oscillation.

In the present study thermocapillary convection in the liquid bridge of a low Pr material, tin, is investigated and the preliminary results are reported here. To the best of our knowledge, thermocapillary convection has not yet been studied in low Pr materials in the configuration of a liquid bridge.

EXPERIMENTAL PROCEDURE

Tin was selected as the material for study in view of its relatively low melting point and well documented physical properties, as shown in Table 1(2-4).

The liquid tin bridge was held between two vertical coaxial iron rods of 4.5 mm diameter. Iron is chemically compatible with molten tin. The rods were heated by two independent heaters. The temperature difference across the liquid bridge was indicated by the two thermocouples at the ends of the rods. A third thermocouple was pushed with a micrometer screw into the liquid bridge from the side to detect temperature and hence flow oscillation. The temperature of the third thermocouple was recorded with a strip chart recorder. All three thermocouples were of the K type.

The experiment was conducted in a vacuum chamber (up to 10^{-6} torr) in order to prevent oxidation.

More details of the experimental procedure will be reported elsewhere due to space limitation.

RESULTS AND DISCUSSION

The tin liquid bridge was axisymmetric ; the molten tin wetted the iron rods properly. The liquid bridge was stable and its free surface was shiny.

Figure 2 shows the result of the temperature measurement in the liquid bridge. The distance between the rods was 4.6 mm. The temperatures of the upper and lower rods were 325 and 240°C, respectively. The tip of the thermocouple was 3 mm above the lower rod and 1 mm into the liquid bridge.

As shown in Fig. 2, the evidence of flow oscillation is clear. The temperature oscillates at the amplitude of around 1.3 °C and the frequency of around 5 Hz. Since the strip chart recorder was already running at its maximum paper speed, however, the time scale could not be enlarged further to reveal more details of the oscillation.

The Marangoni and Bond numbers are defined as follows:

$$Ma = -(\partial\gamma/\partial T)(L\Delta T/\mu\alpha) \quad (1)$$

$$Bo = -\beta\rho g L^2/(\partial\gamma/\partial T) \quad (2)$$

where ΔT is the temperature difference between the upper and lower rods, L the characteristic length, μ the viscosity of the fluid, α the thermal diffusivity of the fluid, β the thermal expansion coefficient of the fluid, ρ the density of the fluid and g the gravitational acceleration.

Based on the physical properties given in Table 1 and the rod radius as the characteristic length L, the Marangoni and Bond numbers for the tin liquid bridge are 488 and 0.33, respectively.

In our previous studies(5-7) we have investigated thermocapillary convection in silicone oil bridges similar to the present liquid tin bridge in size. Computer simulation and flow visualization both confirmed that, as in μg, thermocapillary convection dominates under 1g in these silicone oil bridges. According to Eqns. (1) and (2), the Bond number for tin (0.33) is lower than that for silicone oil (0.79). As such, thermocapillary convection is expected to dominate in the tin liquid bridge in the present study.

CONCLUSION

A liquid bridge of tin was held between two vertical coaxial iron rods 4.5 mm in diameter and 4.6 mm apart. Flow oscillation was observed at a temperature difference of 85°C. The amplitude and frequency of oscillation were around 1.3 °C and 5 Hz, respectively.

FUTURE PLANS

Study on flow oscillation in tin liquid bridge will continue. A data acquisition and processing system will be used to better analyze the experimental results. The critical Marangoni numbers for the onset of flow oscillation will be determined.

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TABLE 1
Physical Properties of Tin (2) and Silicone Oil (3,4)

Properties	Sn	Silicone Oil (5cs)
T_m, °C	232	-
γ, dyne cm^{-1}	560	18.7
ρ, g cm^{-3}	6.98	0.913
$\frac{\partial \gamma}{\partial T}$, dyne cm^{-1} °C^{-1}	-0.09	-0.06
$\beta = \frac{-1}{\rho}\frac{d\rho}{dT}$, °C^{-1}	0.87x10^{-4}	1.05x10^{-3}
μ, g cm^{-1} sec^{-1}	1.81x10^{-2}	4.57x10^{-2}
k, W cm^{-1} °C^{-1}	0.34	1.09x10^{-3}
C_p, J g^{-1} °C^{-1}	0.25	1.71
$\alpha = \frac{k}{\rho C_p}$, cm^2 sec^{-1}	0.195	6.982x10^{-4}
$Pr = \frac{C_p \mu}{k}$	0.013	71.7

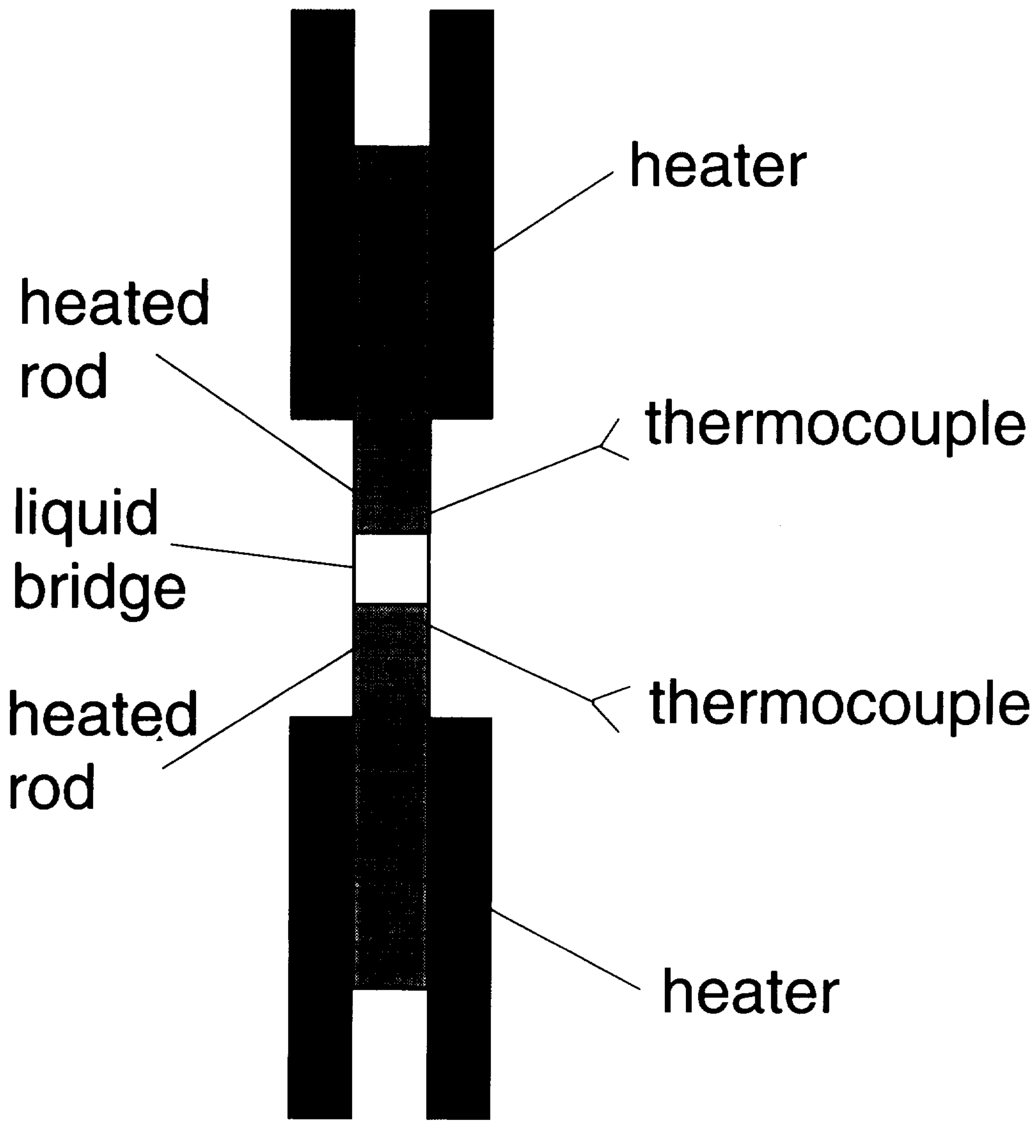

Fig. 1 Liquid bridge.

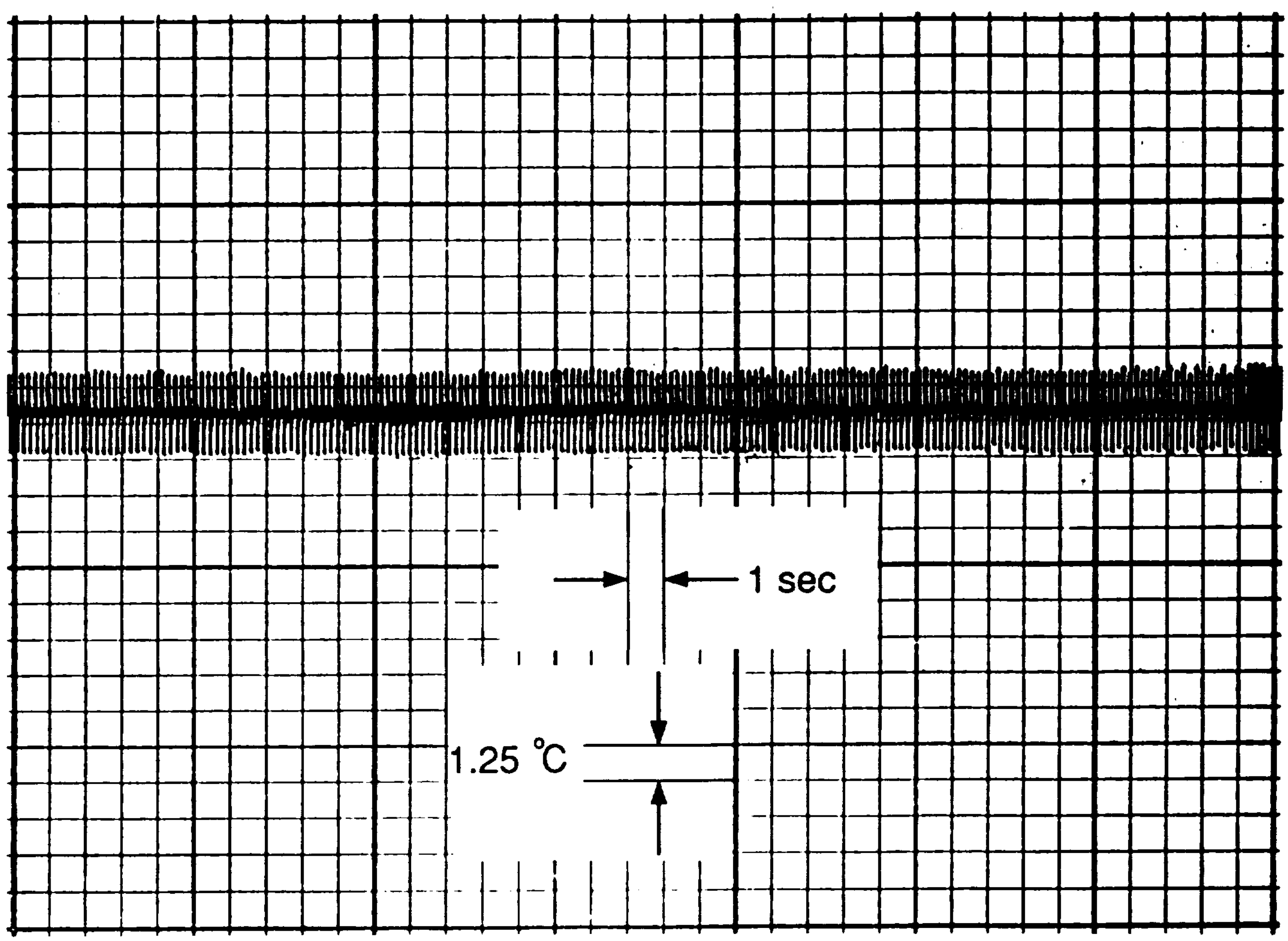

Fig. 2 Temperature oscillation detected in a tin liquid bridge.