1.2 Free Surface Motion Due to Oscillatory Thermocapillary Flow in Liquid Bridges

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FREE SURFACE MOTION DUE TO OSCILLATORY THERMOCAPILLARY FLOW IN LIQUID BRIDGES

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ABSTRACT

Free surface motion in oscillatory thermocapillary flow is investigated experimentally. The flow is generated in small liquid bridges of high Prandtl number fluids. Based on the local measurement of free surface motions and the measurement of liquid column profiles, three-dimensional free surface motions in the oscillatory flow are constructed. The result shows the existence of organized surface waves. The surface waves are shown to be synchronized with thermal waves.

INTRODUCTION

Oscillatory thermocapillary (or Marangoni) flow in the so called half-zone (or liquid-bridge) configuration, in which a liquid column is suspended between two differentially heated circular ends, has been studied by many investigators, mostly for high Prandtl number fluids (reviewed in Preisser et al., 1983; Masud et al., 1997). Much information is available from those studies concerning the flow and temperature fields in oscillatory thermocapillary flows. However, the cause of oscillations is not yet fully understood. Our past work suggests that free surface deformation is important in the case of oscillations in high Prandtl number fluids. The free surface motion of a liquid column during oscillations is generally very small so that it has been neglected by many investigators in the past oscillatory flow studies. However, according to our physical model of oscillations (Kamotani and Ostrach, 1998), the deformation, albeit small, can change the thermocapillary driving force by a sufficient amount to trigger oscillations.

The objective of the present work is to investigate the motion of free surface in oscillatory flow of high Prandtl number fluids. Free surface motion was measured in oscillatory Marangoni flow in the past: Hu et al. (1992) and Shu et al. (1993) in liquid bridges, and Lin et al. (1995) and Kamotani et al. (1999) in open cylindrical containers. The work by Kamotani et al. (1999) was performed in microgravity. All those studies showed the existence of organized free surface motions during oscillations. The objective of the present work is to investigate how those surface waves are related to the flow and temperature oscillations.

DESCRIPTION OF EXPERIMENT

The present test apparatus to produce a liquid column of specified dimensions is the same as the one used in our past experiment (Masud et al., 1997). The diameter of the liquid column is 2 mm and its length is variable. The test fluids are 2 and 10 centistokes (cSt) silicone oils. In order to determine free surface deformation, two techniques are employed. A diffuse light source is placed behind the liquid bridge so that the free surface profile is clearly defined by light contrast, and a microscope (Carl Zeiss Model Stemi SV11) is used to observe the profile. A CCD camera is attached to the microscope and the video image is analyzed using image analysis software. The liquid column is magnified by about 500 times or smaller on a high-resolution monitor so that the smallest deformation we can measure is about 1μm over a 0.4 mm length of the column. The experimental arrangement with the microscope is sketched in Fig. 1.

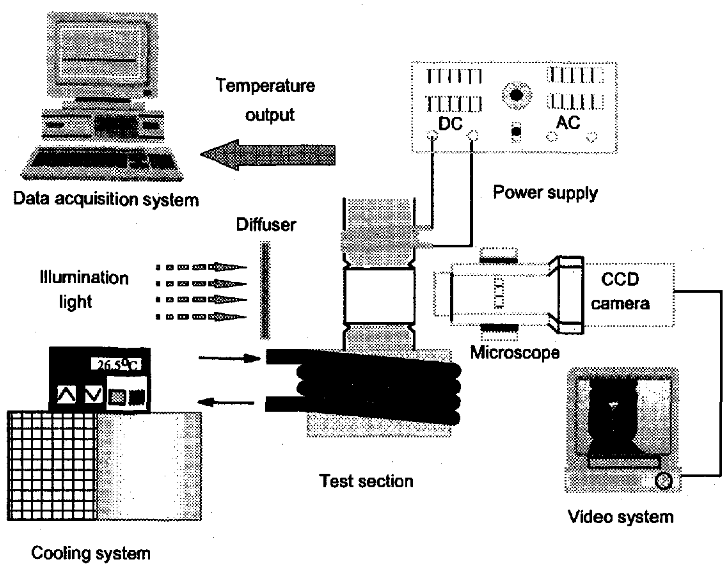


Fig. 1 Experimental arrangement with microscope

Free surface deformation is also measured locally by a laser displacement meter (Keyence Corp. Model LC-2430). Its measuring area is 30 x 20 μm and the resolution is 0.02 μm. Sometimes two sensors are used to determine the phase relation of surface motions at two points. A scanning infrared imager (described in Pline (1988)) is used to determine the temperature wave patterns during oscillations.

IMPORTANT DIMENSIONLESS PARAMETERS

The important dimensionless parameters for steady thermocapillary flow in the presence of buoyancy are: Marangoni number $Ma= \sigma_T \Delta TL/\mu\alpha$, dynamic Bond number $Bd=\rho g\beta L^2/\sigma_T$, Prandtl number $Pr=\nu/\alpha$, and aspect ratio $Ar=L/D$, where ΔT is the imposed temperature difference (T_h - T_c), L is the column length, D is the column diameter, μ is the fluid dynamic viscosity, ν is the kinematic viscosity, α is the fluid thermal diffusivity, ρ is the density, β is the volumetric expansion coefficient, and σ_T is the temperature coefficient of surface tension. Static liquid column shape is determined by the static Bond number $Bo= \rho gL^2/\sigma$ and the total fluid volume which is made dimensionless as the volume ratio Vr=total volume/total volume for cylindrical column. In the present work we minimize the effects of gravity and buoyancy by minimizing Bd and Bo.

In the present experiment Vr is close to unity, and Ar ranges from 0.4 to 0.8. For the largest column length (L=1.6 mm), Bd is 0.35 and Bo is about 1.1. Although Bo is not less than unity, the static column shape is observed to be nearly cylindrical, as shown in Figure 2. According to the experiments by Schwabe and Scharmann (1984), there is no appreciable difference between the critical temperature difference for the onset of oscillations in normal gravity and that in reduced gravity even when Bd is as large as 0.8 in 1-g. Therefore, one can conclude that the effects of gravity and buoyancy are not significant in the present experiments. The fluid viscosity is a function of temperature. In the oscillatory flows investigated herein the value of Pr for 2 cSt fluid ranges from 23.5 to 27.4, and that for 10 cSt fluid ranges from 42.6 to 69.4, where the viscosity is evaluated at $\frac{1}{2}(T_h + T_c)$. The ranges of Ma, based on the average viscosity, are: $Ma \leq 3.9 \times 10^4$ with 2 cSt fluid and $Ma \leq 3.3 \times 10^4$ with 10 cSt fluid.

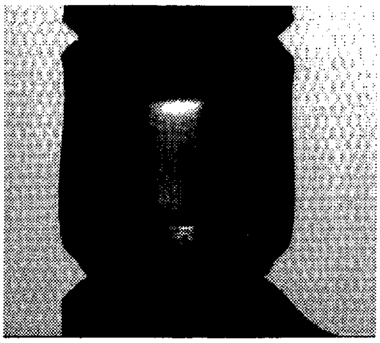


Fig. 2 Liquid free surface shape for D=2 mm and Ar = 0.8 (Bo=1.1)

RESULTS AND DISCUSSION

It is known that the thermocapillary flow in a liquid bridge becomes time-dependent beyond a certain critical ΔT (called ΔT_{cr}), and the flow and temperature fields oscillate in time and space. The values of ΔT_{cr} measured in the present experiments are shown in Fig. 3. As the figure shows, ΔT_{cr} is nearly constant, 17 ± 2 °C, beyond Ar of about 0.55. The velocity and temperature fields during oscillations have been investigated in detail in the past (e.g. Preisser et al., 1983).

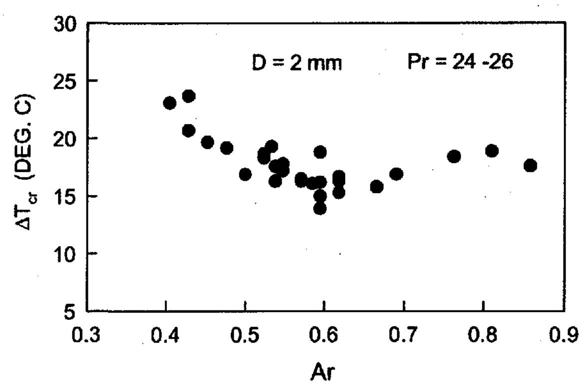


Fig. 3 Critical temperature difference vs. aspect ratio

The main objective of the present work is to investigate the motion of free surface during oscillations. One example of the laser displacement meter output is shown in Fig. 4 for 10 cSt fluid. The figure shows that, as with the velocity and temperature fields, the free surface deforms in periodic manner, with the amount of deformation being on the order of a few μm.

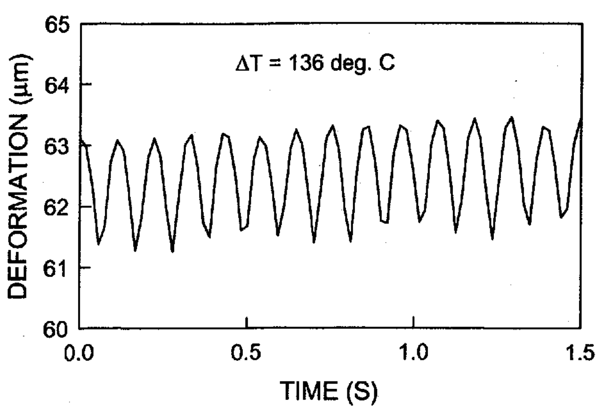
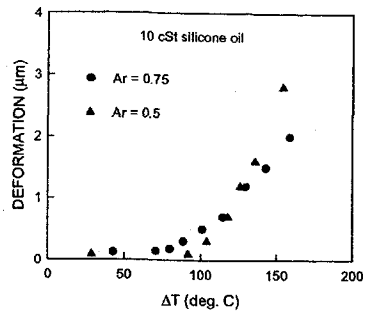


Fig. 4 Free surface deformation during oscillations for 10 cSt silicone oil (Pr=46)

The average peak-to-peak free surface deformation is shown in Fig. 5 at various values of ΔT for the two test fluids. With increasing ΔT, the meter output remains at its noise level until the onset of oscillations, after which the free surface oscillation amplitude increases with ΔT. The deformation for 10 cSt fluid is larger than that for 2 cSt fluid mainly because the range of ΔT is larger for the former fluid.



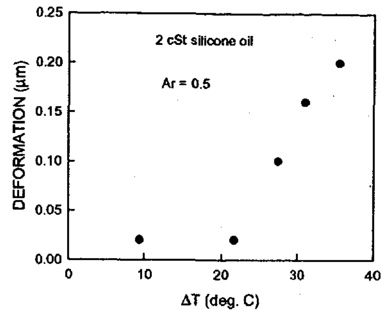


Fig. 5 Amplitudes of free surface deformation at various temperature differences

Observation of liquid surface profiles by the microscope shows that the amplitude and phase of the free surface oscillations vary along the length of liquid column, suggesting the existence of free surface waves. In order to construct the wave pattern we use two laser displacement meters to determine the phase relations of surface oscillations at two different points on the liquid free surface. Free surface oscillation patterns measured by two sensors that are 90 degrees apart in the azimuthal direction near the column mid-height are presented in Fig. 6. In the case of Ar=0.75, the two outputs are about 90° out-of-phase on the average, while they are 180° out-of-phase for Ar=0.45. The phase relation at diametrically opposed locations, namely 180 degrees apart, can be determined by free surface observation. It is not possible for the microscope to detect small free surface deformations if its magnification is reduced to see the complete liquid column shape, so we project the whole liquid column profile on a big screen to determine the phase relation at two opposite locations.

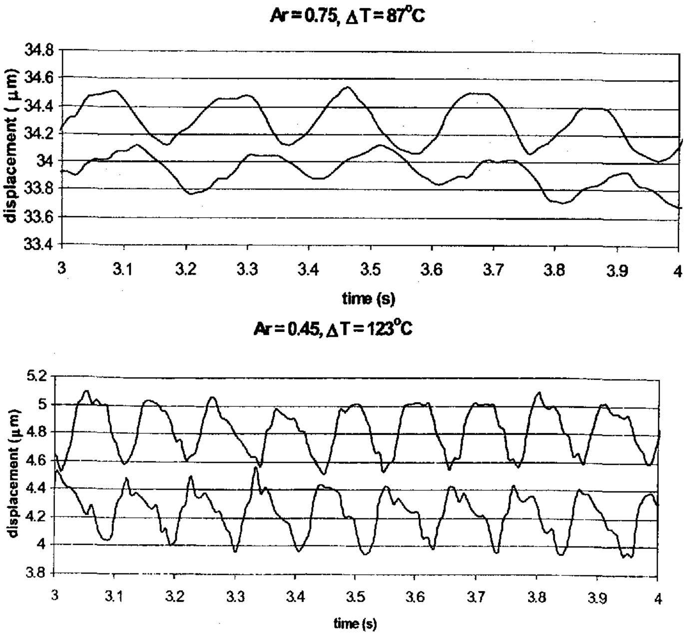


Fig. 6 Phase relations of surface deformation at two locations 90 degrees apart for 10 cSt silicone oil

The observation shows that if Ar is larger than 0.5, the azimuthal wave number of the traveling surface wave is one near the onset of oscillations and if Ar is less than 0.5, the wave number is two, which is in agreement with the results of Fig. 6.

The infrared images of free surface show that a thermal wave is traveling around the column axis with the same wave number as the corresponding free surface wave for a given Ar. A typical thermal wave pattern, represented by the isotherm pattern obtained from the infrared images of free surface, is sketched in Fig. 7 (the azimuthal wave number is 1 in the figure). The main feature of oscillatory flow is that the flow along the free surface in a given radial (or meridional) plane becomes alternately strong and weak in one cycle (Kamotani and Ostrach, 1998). The period when the surface flow is strong (weak) is called active (slow) period. In an active period, the convection from the hot to the cold end along the free surface increases and a hot wave front spreads from the hot end towards the cold end. In a slow period, the surface temperature decreases. The pattern also rotates around the column axis, resulting in the isotherm pattern shown in Fig. 7 at a given time.

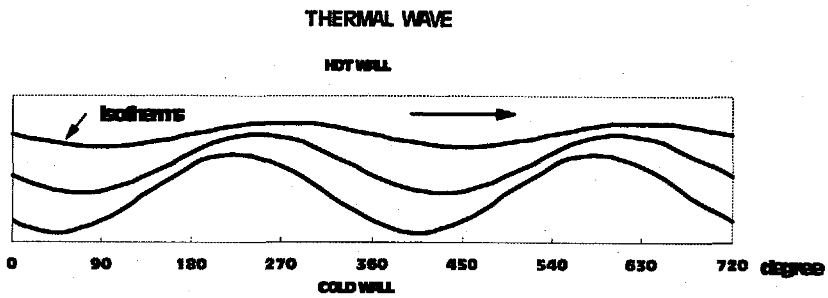


Fig. 7 Thermal wave propagation over free surface in oscillatory flow

Based on various comparisons of local surface and thermal oscillation patterns, the phase relation between two traveling waves at a given point is illustrated in Fig. 8. As discussed above, the fluctuating part of surface temperature is positive (negative) during an active (slow) period. As the temperature becomes positive, the surface begins to move down, reaches the lowest point at the end of an active period, and then begins to move up when the surface temperature becomes negative (slow period). That result suggests that the azimuthal temperature gradients caused by the thermal waves

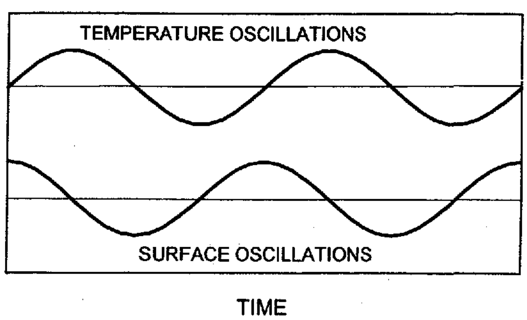


Fig. 8 Phase relation between temperature and surface oscillations at a given point on free surface

generate secondary thermocapillary flow in the azimuthal direction from the hot to the cold region, so that the fluid is removed from the hot region and accumulates in the cold region. The gradients of free surface temperature distribution determine the thermocapillary driving force. The main driving force is in the axial direction (from the hot to the cold wall) in the present problem. It is known that the main driving force is very large near the hot and cold walls but relatively small near the mid-height of the liquid column in the parametric range of the present experiments (Kamotani and Ostrach, 1998). Consequently, the secondary driving force in the azimuthal direction discussed above is relatively important near the mid-height, so that the free surface oscillations are observed to be relatively large in that region.

By putting all the information together we have the following picture. In an active period of an oscillation cycle in a given radial plane, the surface flow becomes strong, the surface temperature increases, and the free surface recedes. The opposite happens in a slow period. The pattern also rotates around the column axis. The resulting free surface wave pattern, represented by contour lines, is sketched qualitatively in Fig. 9. It is important to note that the surface wave depicted in Fig. 9 is a result of the thermal wave propagation and, as such, it may not be actively involved in the cause of oscillations. According to our concept of oscillation mechanism, the motion of free surface close to the hot wall (called hot corner) and its relation to the thermal boundary layer along the hot wall are important. But, a detailed study in the hot corner is left for future work.

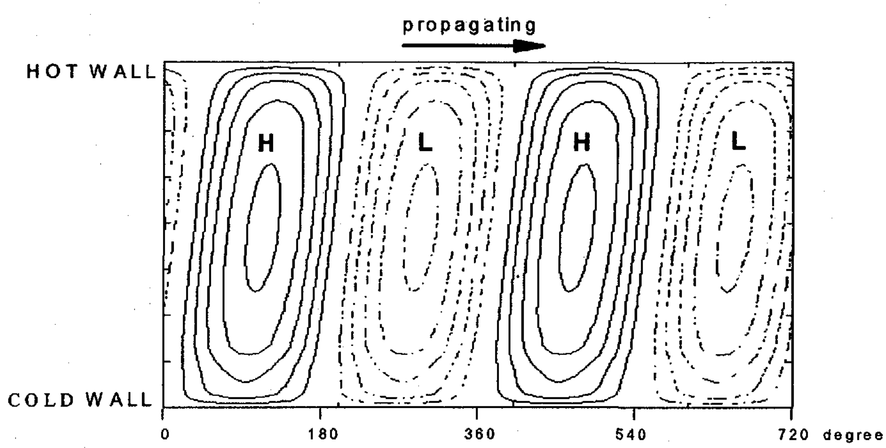


Fig. 9 Propagation of surface wave in oscillatory flow (H=peak, L=valley)

CONCLUSIONS

Free surface waves and thermal waves are measured in oscillatory Marangoni flows in cylindrical liquid columns of high Prandtl number fluids. Waves traveling in the azimuthal direction, having wave numbers of one and two, are found. The relation between the surface and thermal waves are determined.

ACKNOWLEDGMENTS

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