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The effect of small vibrations on Marangoni convection and the free surface of a liquid bridge

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Abstract

The effects of small vibrations on Marangoni convection were investigated experimentally using a liquid bridge of 5 cSt silicone oil with a disk diameter of 7.0 mm, and an aspect ratio close to 0.5. Experiments were performed to determine the critical temperature difference data for no vibration case and with small vibrations applied. The experimental results have shown that the effect of small vibrations on the onset of oscillatory flow is small since the critical temperature difference data for different aspect ratios were not affected by the vibrations. To clarify the surface oscillation phenomena induced by external vibrations, a 3-D numerical simulation model was also developed using a level set algorithm to predict the surface oscillations of isothermal silicone oil bridges. By subjecting the liquid bridge to small vibrations, the surface oscillation characteristics were predicted numerically, and the numerical results compared well with the predictions of an analytical model proposed previously. Furthermore, the effect of small vibrations on the surface vibration amplitude of the liquid bridge is also discussed.

Keywords: Liquid bridge; Vibration; Free surface; Marangoni convection; Level set

1. Introduction

Marangoni convection in liquid bridges can change from a steady, axi-symmetric flow to an oscillatory flow, when a sufficiently large temperature gradient is imposed [1,2]. Such an oscillation in flow can lead to non-uniformities in crystal structure such as striations [3] when a floating zone process is used to fabricate single semiconductor crystals of high purity from melts. Large liquid bridges can be formed under microgravity in space [4], however, the liquid bridges are also susceptible to small vibrations or g-jitter on space platforms that may excite oscillations of the free surface and add to the complexity of the hydrodynamics involved. Small vibrations or g-jitter are caused by operation of various on-board devices, the physical activities, thruster firings for spacecraft attitude control and so on. g-Jitter contains a wide spectrum of vibration frequencies. The liquid bridge may have one or more resonance frequencies within such a wide range of vibration frequencies and its free surface may oscillate dynamically with very high amplitudes, even though the imposed vibration amplitude is very small. The dynamic vibration of the free surface may in turn affect the onset of oscillatory Marangoni convection. Thus, studying the surface

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behavior of the liquid bridge is of great importance in preventing the unwanted consequences of g-jitter.

For axisymmetric liquid bridges, Sanz [5] analyzed the resonance mode of an axisymmetric liquid bridge surface for an axial disturbance using an inviscid assumption and compared the predictions with experimental results obtained for a slender liquid bridge formed in the Plateau-tank. Tsamopoulos et al. [6] extended the analysis of Sanz by including the effect of viscosity. Chen et al. [7] and Mollot et al. [8] investigated theoretically and experimentally the resonance frequency and damping ratio of a liquid bridge, respectively. For non-axisymmetric liquid bridges, Sanz et al. [9] analyzed several axial and lateral resonance modes on the liquid bridge surfaces with an inviscid assumption and compared resonance frequencies corresponding to each mode with the experimental results obtained using the Plateau-tank technique. Ichikawa et al. [10] proposed a model based on a mass-spring-damper system and performed a terrestrial experiment to determine the resonance frequency.

In this work, the effects of small vibrations on the critical temperature difference have been investigated for liquid bridges of 5 cSt silicone oil. The surface oscillation characteristics of isothermal silicone oil bridges have also been investigated numerically by comparing the numerical predictions with the analytical model predictions of Ichikawa et al. [10].

2. Experimental apparatus and instrumentation

A schematic of the test section is shown in Fig. 1. It had upper and lower disks of 7.0 mm diameter made of brass. A type-T micro-thermocouple with a wire size of 25 µm used to detect the liquid temperature was inserted into the liquid bridge suspended between the two disks through a hole in the upper disk. Type-T thermocouples were also used to measure the temperature of each individual disk. The temperatures of the upper and lower disk were controlled by a circulating water-bath with heating and cooling circuits. In addition a Peltier element was attached to the lower disk. By changing the applied voltage to the Peltier element, the lower disk temperature could be finely controlled. A PC-controlled vibration stage (Parker-Daedal Model 404XR150MP) was employed to apply horizontal vibrations to a liquid bridge and find the effect on the critical temperature difference at the onset of oscillatory Marangoni convection, as well as the free surface response. The test section was mounted on the stage, which was translated horizontally at a constant speed. Due to friction effects, however, small vibrations in all directions were experienced by the liquid bridge as detected by an accelerometer. A video camera and a single-axis accelerometer were mounted on the same stage to monitor the liquid bridge's surface vibration and acceleration level, respectively. The fluid used to form a liquid bridge between the upper and lower disks was a 5 cSt silicone oil.

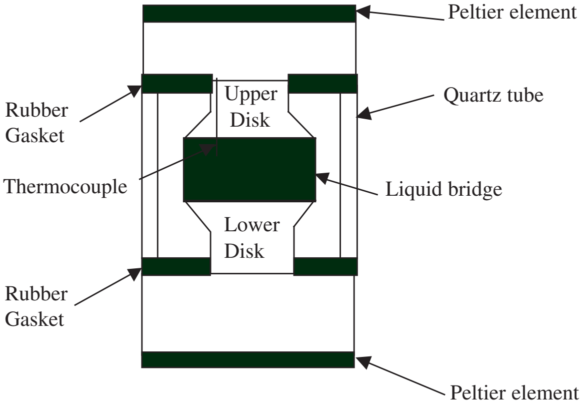

Fig. 1. Schematic of the test section.

3. Numerical simulation

3.1. 3-D governing equations

The equations of motion for an incompressible flow including gravitational and small horizontal acceleration forces, viscous, and surface tension effects are given by the following incompressible Navier–Stokes equations

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0, \tag{1}$$

$$\begin{aligned}\frac{\partial u}{\partial t}= & -u\frac{\partial u}{\partial x}-v\frac{\partial u}{\partial y}-w\frac{\partial u}{\partial z}+\mathrm{FGX}\\ & +\frac{1}{\rho}\left(-\frac{\partial p}{\partial x}+\frac{\mu}{Re}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)\right.\\ & \left.+\frac{1}{We}\kappa\delta(d)\mathbf{n}\right),\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{\partial v}{\partial t}= & -u\frac{\partial v}{\partial x}-v\frac{\partial v}{\partial y}-w\frac{\partial v}{\partial z}\\ & +\frac{1}{\rho}\left(-\frac{\partial p}{\partial y}+\frac{\mu}{Re}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)\right.\\ & \left.+\frac{1}{We}\kappa\delta(d)\mathbf{n}\right),\end{aligned} \tag{3}$$