 FDMP, vol.6, no.1, pp.99-108, 2010

Effect of Ambient-Gas Forced Flow on Oscillatory Thermocapillary Convection of Half-Zone Liquid Bridge

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Abstract: The authors focus on thermocapillary-driven flow in a half-zone liquid bridge and its transition from two-dimensional steady flow to three-dimensional oscillatory one under an effect of forced convection in ambient gas region around the liquid bridge. The liquid bridge is settled in a cylindrical 'external shield,' in which upward/downward forced flow of the ambient gas is added. The critical condition of the flow transition in the 2-cSt silicone-oil liquid bridge is examined as functions of the aspect ratio and the volume ratio of the liquid bridge, and averaged velocity of the ambient gas. The authors indicate a significant effect of the external flow around the liquid bridge.

Keywords: Liquid bridge, ambient gas flow, flow transition.

1 Introduction

A long-duration on-orbit fluid physics experiment on "Kibo," the Japanese Experimental Module, aboard the International Space Station had been successfully carried out from August to October in 2008 (Kawamura, Nishino, Ohnishi, Ueno & Matsumoto (2008)). Thermocapillary-driven flow in a half-zone liquid bridge of 30 mm in diameter and its critical condition of flow transition are examined. That series of experiments indicates an invaluable knowledge on the effects of the gravity and the size of the liquid bridge itself. Recent works, on the other hand, have revealed a significant effect of heat transfer between the liquid bridge and the ambient gas region on the critical condition by experiments (Kamotani, Wang, Hatta, Wang & Yoda (2003), Irikura, Arakawa, Ueno & Kawamura (2005), Mialdun & Shevtsova (2006)) and numerical simulations (Irikura, Arakawa, Ueno & Kawamura (2005), Shevtsova & Melnikov (2006), Tiwari & Nishino (2007)). That is,

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the critical condition is very sensitive to the thermal boundary condition on the free surface of the liquid bridge. In the present study, the authors put an external shield around the liquid bridge, in which a flow-rate controlled forced convection of ambient gas is realized to investigate the effect of the thermal/mechanical stresses over the free surface on the thermocapillary-driven in the half-zone liquid bridge.

2 Experiments

Experimental setup is illustrated in Fig. 1. This setup is composed with three major parts; a part for liquid bridge formation, a part for realizing a forced convection in the shield, and a part for measurement. The formation part of the half-zone liquid bridge is based on the one introduced in Ref (Ueno, Tanaka & Kawamura (2003)).

A liquid bridge is formed between coaxial cylindrical rods of 5 mm in diameter. Distance of the gap between the end surfaces of the rods is fixed at 1.6 mm, thus the aspect ratio of the liquid bridge, Γ $(= H/R)$, is kept constant at 0.64, where H and R are the height and the radius of the liquid bridge, respectively. The ratio of the volume of the examined liquid bridge to that of the straight cylinder of H in height and R in radius, V/V_0 $(= V/(\pi R^2 H))$, is fixed at unity. The flow in the liquid bridge of this geometry without adding any forced convection in the ambient air exhibits an oscillatory flow with m = 3, where m is the azimuthal mode number (Ueno, Tanaka & Kawamura (2003)). Test fluid in the present study is 2-cSt silicone oil. Top rod is made of transparent sapphire, which enables the authors to observe the flow field in the bridge through the rod. The edge of the bottom rod made of aluminum is sharp-tapered to sustain the contact line of the liquid bridge. The side surface of the bottom rod is chemically coated for anti-wetting by the test fluid. Temperature difference between the rods, ΔT, is realized by heating the top rod to maintain its temperature at T_H and cooling the bottom at T_C. Intensity of applied thermocapillary effect to the liquid bridge is described with Marangoni number defined as $Ma = \sigma_T \Delta T H/(\rho \nu \kappa)$, where σ_T is the temperature coefficient of the surface tension $(= |\partial\sigma/\partial T|)$, ρ the density, ν the kinematic viscosity, and κ the thermal diffusivity. The part of the liquid bridge formation is completely wrapped by placing the external shield made of Pyrex® glass of 1.5 mm in thickness. The inner diameter of the external shield $D_{ES} = 2R_{ES}$ is of 25 mm. The external shield is hold by the shield holders made of aluminum. Each shield holder has four channels for inlet/outlet of the ambient gas flow. The direction of the external flow, that is, upward or downward, is able to be varied. A diffuser is placed right after the inlet and before the external shield to realize a uniform flow field inside the shield. The flow field in the external shield is described with an averaged velocity $U_{avg} = Q/\pi(R_{ES}^2 - R^2)$ and non-dimensional Reynolds number $Re = U_{avg} L/\nu_{air}$, where Q is the controlled flow rate in the external shield, L the hydraulic diameter of the granular channel (= $2R_{ES} - 2R$), and ν_{air} the kinematic viscosity of the air. In the present study, upward forced flow in the external shield is defined as positive. Test fluid for ambient gas is a dried air at 25 ˚C.

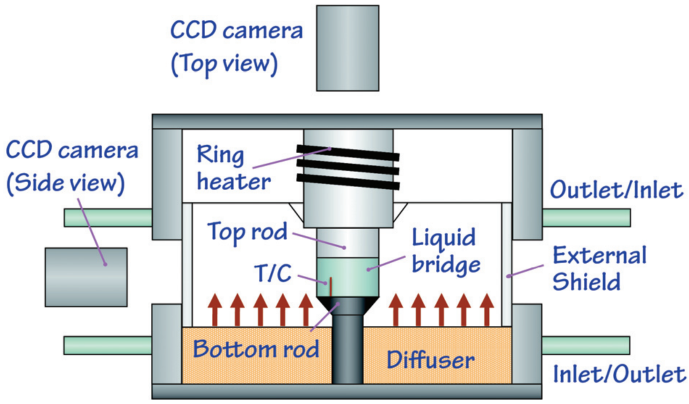

Figure 1: Experimental apparatus. Case of upward forced convection in the external shield is described. In the case of downward convection, the diffuser is located upper part of the top rod, and the top channel becomes 'Inlet' and the bottom 'Outlet.' Another thermocouple is omitted in the figure.

The flow field of the ambient air is visualized by adding incense smoke. The incense smoke is prepared and stocked in a storage tank to keep at room temperature. A mixture of the air and the incense smoke is drawn to the test section through the mixing valve as the ambient gas. A vertical sheet of laser light of 633 nm in wavelength is irradiated through the external shield. The power of the laser is of 10 mW, thus the irradiation of the laser light sheet would never affect the flows in the liquid bridge nor of the ambient gas. Refraction of the laser light sheet is relatively small because of the rather large radius of the external shield. The flow field of the ambient air is recorded with a high-speed CCD camera of 250 fps in frame rate through the external shield. The incident angle of the CCD camera is perpendicular to that of the laser light sheet.

The flow field in the liquid bridge is also observed with another high-speed CCD camera synchronized with the CCD camera for the side view through the transparent top rod as the top view. The flow in the bridge is visualized by suspending gold-coated acrylic sphere particles of 15 μm in diameter. Whole liquid bridge is irradiated by a cold light through the transparent top rod. Detailed information in the flow visualization inside the liquid bridge is indicated in Ueno, Tanaka & Kawamura (2003). This system enables the authors to observe the flow fields of the ambient air in the laser light sheet and of the liquid bridge simultaneously.

Temperature inside the liquid bridge is monitored with two Cr-Al thermocouples of 25 μm in diameter inserted through the bottom rod. The positions of the tips are fixed at R/2 from the center of the bridge and at H/2 from the bottom rod surface. The thermocouples are located with a 90° interval in the azimuthal direction. This alignment prevents the both thermocouples fall onto the nodes of the standing-wave oscillation of m = 3. The authors pick out a time series of temperature inside the liquid bridge with larger amplitude for analytical procedure. This system enables the authors to avoid any unintended disturbances resulting in non-uniform external thermo-fluid condition around the liquid bridge. It should be noted that the onset of the oscillation was preliminarily monitored with three different ways, that is, the temperature oscillation on the free surface of the liquid bridge, the particle motion observed from the top rod, as well as the temperature oscillation inside the liquid bridge. The temperature of the liquid bridge surface is measured with a Cr-Al thermocouple of 25 μm in diameter, which is placed in the vicinity of the bridge free surface without touching it at H/2 in height (mid-height of the liquid bridge). This measuring process is the same measurement system as described in Ueno, Tanaka & Kawamura (2003). The authors have convinced themselves that the evaluated critical points with those ways are almost the same, and that the most favorable wave number m after the onset of oscillation never changes with inserting thermocouples inside the bridge.

3 Results & Discussions

Critical condition in the liquid bridge is illustrated in Fig. 2. The critical condition is described as the critical Marangoni number Ma_c as a function of Re and U_{avg}. The critical Marangoni number in the case of naked liquid bridge, that is, without the external shield is also plotted. It is noted that the favourable wave number after the onset of oscillation, m,

never changes in the present range of the experiments; the present liquid bridge exhibits an oscillation with m = 3 as indicated by Ueno, Tanaka & Kawamura (2003) in the case of without the external shield. In the case of adding upward forced flow ($U_{avg} > 0$), the flow in the liquid bridge becomes slightly unstable, that is, the critical Marangoni number slightly becomes smaller. And the critical value converges into a constant value in the present experimental range. In the case of downward forced flow ($U_{avg} < 0$), on the other hand, the flow in the liquid bridge becomes more stable by increasing the velocity.

Snapshot of the flow in the ambient air region near the free surface of the liquid bridge is presented in Fig. 3. The flow is observed from the side through the

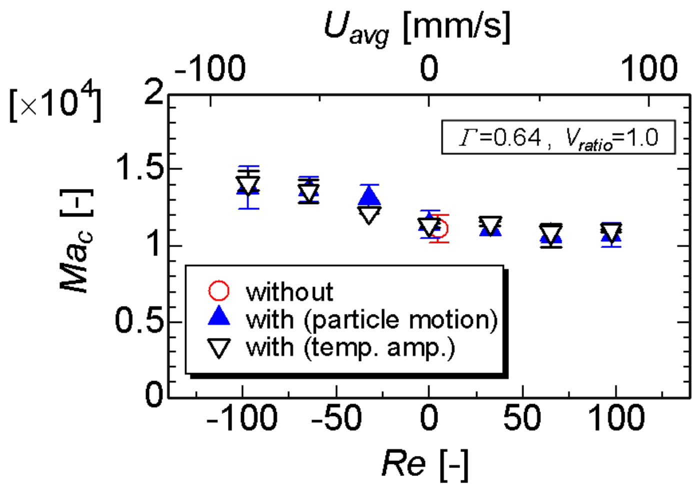

Figure 2: Critical condition of the onset of the oscillatory flow in the liquid bridge as a function of the Reynolds number of the ambient-gas flow; triangle mark indicates the evaluated Ma_c judged by the suspended particle motion, and the inverted triangle mark that judged by the temperature oscillation inside the liquid bridge. Circle mark indicates the evaluated Ma_c in the case of naked liquid bridge (without the external shield) judged by the inner temperature oscillation.

transparent external shield. The inner wall of the external shield is out of the field of view in both side of the bridge. The figures illustrate the flow near the onset of the oscillation in the liquid bridge. Without any forced flow in the ambient gas region as shown in (a), the thermocapillary-driven flow over the free surface of the liquid bridge drives the ambient gas to form double vortices of about R/4 in size in the horizontal direction around the bridge. The vortex near the bottom rod stretches itself below the surface of the bottom rod. A significant upward flow is observed in the bulk region of the ambient air, which is driven by a buoyant flow as generally seen in the case of the naked liquid bridge (Irikura, Arakawa, Ueno & Kawamura (2005)). Note that the vortex formation and its size under the present size of the external shield are almost the same as the case of the naked liquid bridge. In the case of upward forced convection as shown in (b), the vortices around the liquid bridge do shrink their size, which result in enhancement of the heat transfer between the liquid bridge to the ambient air. In the bulk region of the ambient air, an inclined upward flow is realized because of the edge of the bottom rod. This also results in smaller vortex near the bottom rod. In the case of downward forced convection as shown in (c), on the other hand, vortices disappear around the liquid bridge to form almost uniform external flow in the ambient air region. It is noted here that the axial velocity on the free surface of the liquid bridge due to the thermocapillary effect is of about 10 mm/s under the present condition. That is, the forced convection in the ambient air is much faster than the themocapillary-driven one. The forced flow in the ambient air might accelerate the free surface because of the mechanical stress. The fluid flowing over the free surface penetrates into deeper region toward the center of the bridge, which is confirmed by the observation of the flow in the liquid bridge through the top rod.

One can extract valuable information through the thermal field of the liquid bridge, especially of the high Prandtl number fluid. Temperature oscillation of the liquid bridge corresponds to the azimuthal structure of the oscillatory flow after the onset of oscillation (Preisser, Schwabe & Scharmann (1983), Ueno, Tanaka & Kawamura (2003)). Noted that any axial oscillation seldom emerges in such a short liquid bridge of $\Gamma = 0.64$. Figure 4 indicates a frequency distribution of the temperature fluctuation inside the liquid bridge at $Ma = 1.1Ma_c$. This means that one has a correlation of $Ma_{(b)} < Ma_{(a)} < Ma_{(c)}$ as shown in Fig. 2. The frames (a) to (c) correspond to the conditions shown in Fig. 3 except the Marangoni number. The oscillatory flow inside the liquid bridge is strongly affected by the ambient-air flow; the fundamental frequency decrease if one adds an upward forced flow (b) comparing to the case of (a). An upward forced flow around the liquid bridge apparently seems to have a deceleration effect against the thermocapillary-driven flow that drives the liquid over the free surface downward (toward the cold rod); the upward flow is added as a counter flow against the surface flow of the liquid bridge. But the upward forced flow in the ambient air region results in accelerating the outer part of the vortices around the liquid bridge, and in confining the vortices in the radial direction. The thin accelerated toroidal vortices bring strong shear force and enhanced heat transfer between the bridge and the ambient air, which destabilize the flow inside the liquid bridge. If one adds a downward forced flow in the ambient-air region (c), on the other hand, the fundamental frequency increases comparing to the case of (a). As shown in Fig. 3 (c), the downward forced flow prevents a formation of vortices around the bridge; the forced flow in the ambient air does accelerate the free surface because of the mechanical stress, thus the fluid flowing over the free surface penetrates into deeper region toward the center of the liquid bridge. In addition, the heat loss effect is much weaker than the upward flow case; the temperature of the air of the downward forced flow is higher than the mean temperature of the liquid bridge because the air is experienced a hot rod before arriving the liquid bridge. Thus the flow in the liquid bridge is stabilized.

The fundamental frequency of the temperature fluctuation inside the liquid bridge under $Ma = 1.1Ma_c$ is plotted in Fig. 5. The fundamental frequency has almost

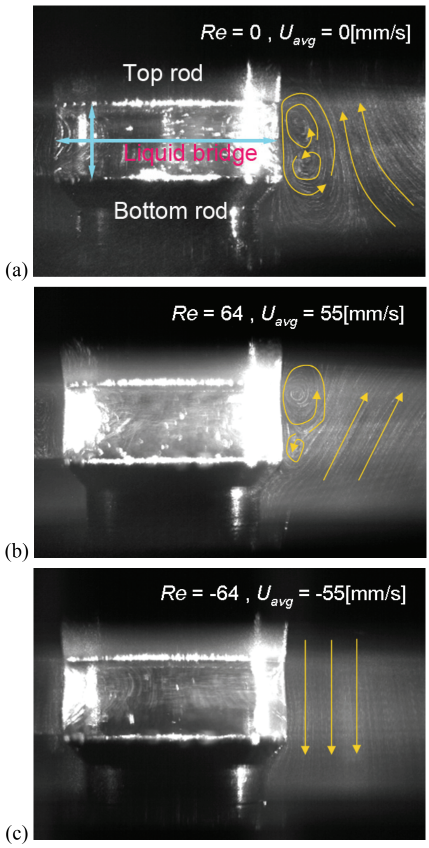

Figure 3: Snapshots of ambient-air flow and the liquid bridge (a) without any forced convection in the external shield (*Re* = 0), (b) with upward forced convection (*Re* = 64), and (c) with downward forced convection (*Re* = -64). The images are obtained by integration for 1.0 s (30 frames).

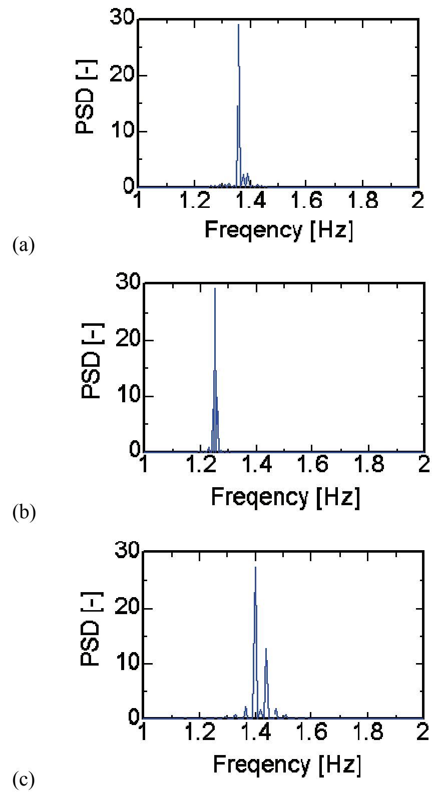

Figure 4: Frequency distribution of the temperature fluctuation inside the liquid bridge at $Ma = 1.1Ma_c$; (a) without any forced convection in the external shield (*Re* = 0), (b) with upward forced convection (*Re* = 64), and (c) with downward forced convection (*Re* = -64). Noted that $Ma_{(b)} < Ma_{(a)} < Ma_{(c)}$ as indicated in Fig. 2.

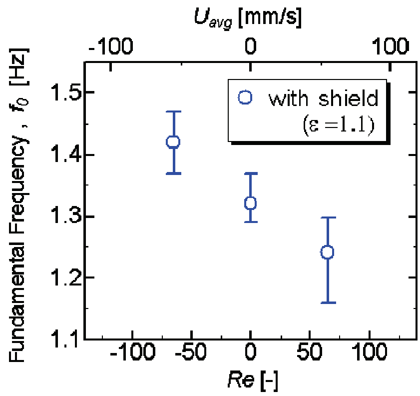

Figure 5: Fundamental frequency of the temperature fluctuation inside the liquid bridge at $Ma = 1.1Ma_c$ against the velocity of the forced flow inside the external shield.

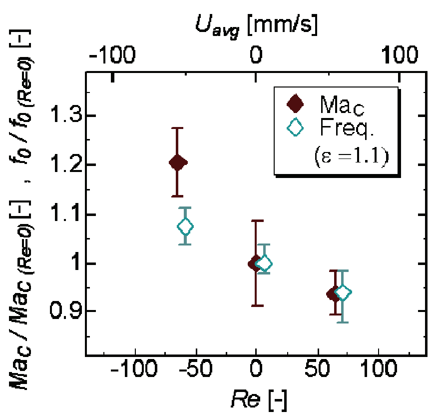

Figure 6: Comparison between the critical Marangoni number Ma_c (as shown in Fig. 2) and the fundamental frequency of the temperature fluctuation inside the liquid bridge at $Ma = 1.1Ma_c$ (as shown in Fig. 5) against the velocity of the forced ambient-air flow inside the external shield. Relative values are plotted to those under $Re = 0$.

linear tendency against the Re of the ambient-air flow. In order to compare the tendencies of the fundamental frequency of the temperature oscillation inside the liquid bridge (as shown in Fig. 5) and the critical condition (in Fig. 2) against the forced flow in the external shield, distributions of the relative frequency and critical Marangoni number to those under $Re = 0$ is illustrated in Fig. 6. In the case of the upward forced flow, the relative variation of the fundamental frequency of the temperature oscillation inside the liquid bridge almost corresponds to the one of the critical Marangoni number. In the case of the downward forced flow, on the other hand, the relative variation of the fundamental frequency is much smaller than that of the critical Marangoni number. Further information on the acceleration effect by the forced ambient-air flow on the axial/radial velocities of the fluid in the liquid bridge is needed. The authors will carry out further research focusing on the affected flow inside the liquid bridge by applying additional measurement systems to extract information of the three-dimensional velocity fields inside/outside the liquid bridge.

4 Concluding Remarks

The authors carry out an experimental study on the thermocapillary-driven flow in the half-zone liquid bridge of 2-cSt silicone oil exposed to a forced convection in the external shield coaxially wrapping the bridge. The effects on the critical condition of the onset of the transition of the flow in the bridge from the two-dimensional steady flow to the three-dimensional oscillatory one and on the thermal fluctuation after the onset are examined. Vortex formation around the liquid bridge due to the forced convection is described based on the observation from the side. The authors also indicate a relation between the critical condition in terms of the critical Marangoni number and the oscillation of the temperature inside the liquid bridge as a function of the flow velocity of the forced ambient-air flow.

Acknowledgement: The authors gratefully acknowledge members of JEREMI (Japan-Europe Research Experiment on Marangoni Instability), Prof. Koichi Nishino (Yokohama National Univ., Japan), Dr. Satoshi Matsumoto (Japan Aerospace Exploration Agency (JAXA)), Dr. Valentina Shevtsova, Dr. Denis Melnikov, Dr. Sacha Mialdun, (Université Libre de Bruxelles), Prof. Dr. Hendrik C. Kuhlmann (Technische Universität Wien), Prof. Dr. Dietrich Schwabe (Justus Liebig-Universität), Dr. Stefano Mazzoni (ESA), and Dr. Jose Maria Montanaro (Universidad de Extremadura), for fruitful discussions. A part of this study is financially supported by JAXA.

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