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Influence of a coaxial gas flow on the evolution of oscillatory states in a liquid bridge

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ABSTRACT

We present an experimental and complementary computational study of a two-phase flow in a liquid bridge that develops under the action of buoyant and Marangoni forces in the presence of a gas stream parallel to the interface. The gas flow is counter-directed with respect to the steady flow in liquid. The forced gas flow along the interface provides actions on the system via shear stresses and heat exchange. For the experimental fluids (n-decane, nitrogen) the ratio of viscosities is large, about 40, and the gas Reynolds number is moderate, $Re_g = 120$. Thus, heat transfer is the prevailing mechanism by which gas affects the flow in a liquid. The effect of gas temperature on the evolution of flow states is examined. The study reveals that in the supercritical region, $\Delta T > 1.25\Delta T_{cr}$, the flow dynamics can be divided in three regimes relative to the gas temperature. When the gas is colder than the temperature of the supporting disk, multiple transitions between the oscillatory states occur: periodic, quasi-periodic with two frequencies, quasi-periodic with three frequencies and noisy quasi-periodic with three frequencies. In the case, when the gas temperature approaches the temperature of the cold disk and goes up to the mean temperature, the flow remains periodic up to the largest tested ΔT. In the case of hotter gas, the flow also remains periodic far above the threshold of hydrothermal instability, but the azimuthal mode of the periodic oscillatory flow is changed. The stability window is found to exist between these two azimuthal modes and its location is sensitive to the gas parameters as well as to the geometry of a liquid bridge. It opens a possibility that oscillatory instability can be stabilized by choosing specific temperatures and velocities of counter-current gas.

1. Introduction

The thermal dependence of surface tension leads to thermocapillary Marangoni stresses that act along the free surface. These stresses are balanced by viscous stresses and the liquid interior is set in motion. In the gravity field, a convective flow evolves by a combined action of the buoyancy and the thermocapillary effect. Here we consider flows in a cylindrical liquid bridge, which is a drop of liquid held by the action of the surface tension force between two solid rods, and the top rod is hotter than the bottom one. A liquid bridge can be regarded as the simplest half-zone model of the floating zone technique of crystal growth. This connection endows the study of liquid bridges with great interest not only in the field of materials engineering but also in fluid mechanics.

An axisymmetric steady flow arises in a liquid bridge as soon as a tiny temperature difference is applied between the supports. This thermoconvective flow becomes unstable when $\Delta T = T_{hot} - T_{cold}$ exceeds some critical value ΔT_{cr} and, in a liquid bridge, for the first time this phenomenon was experimentally confirmed by Schwabe [1]. Recently, he presented historical remarks about the first steps of the exploration of Marangoni convection [2]. An instability sets as Hopf bifurcation and gives rise to a number of time-dependent three-dimensional flow regimes [3]. In particular, it may generate standing or traveling hydrothermal waves or lead to temporally chaotic dynamics [4–6].

The liquid bridge model, which has been actively used so far in theoretical and numerical studies [7–10], is shown in Fig. 1a. It is a one-phase model in which the free interface can be thermally insulated or where heat exchange is prescribed through the Biot number [11,12]. This model allows qualitative comparison with experiments for which a more suitable geometry is shown in Fig. 1b. In the experimental arrangement the liquid bridge is surrounded by gas (e.g., air or nitrogen). To prevent the impact of lab-

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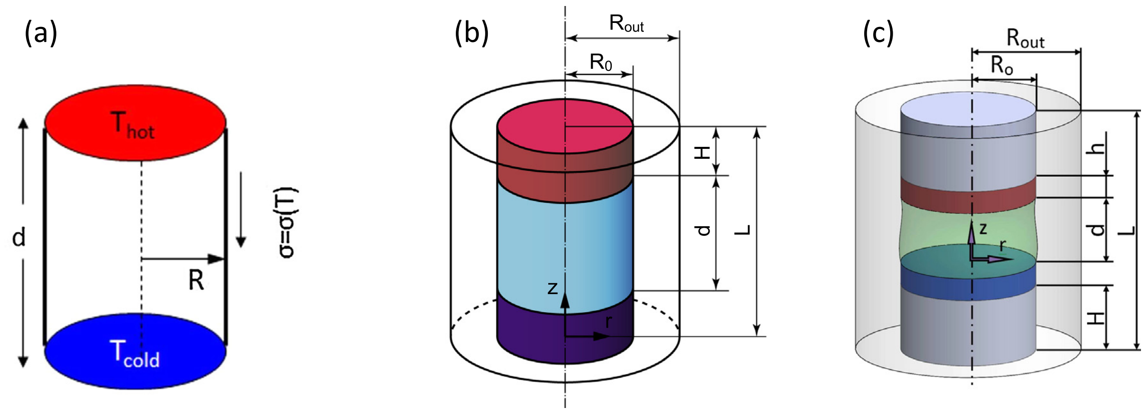

Fig. 1. Geometries of liquid bridges used in numerical simulations and experiments.

oratory air circulation, as a rule, the liquid bridge is surrounded by a co-axial cylinder whose diameter and material largely vary from one to another experiment. The temperature of the gas near the interface is also influenced by the length and diameter of the rods and its distribution significantly affects the flow in the liquid bridge. Although generally the experimental arrangement is similar in any liquid bridge set-up, the particular implementation leads to a strong divergence of the experimental results as it was revealed in the benchmark study [13]. Notice, that all of these above-mentioned models in Fig. 1 can be equally complicated by interface deformation [14].

The first experiments controlling ambient conditions around a liquid bridge [15–18] have indicated that heat exchange between the liquid and the ambient gas is an important factor that defines the instability mechanisms. Subsequent experimental studies related to the influence of ambient conditions were focused on understanding the effect of controlled gas flow in the annular gap between a liquid bridge and the external cylindrical tube. The onset of instability was measured with upward and downward gas flow in a liquid bridge filled with 2 cSt [19,20] and 5 cSt [20] silicone oils at various aspect ratios. In the case of a nearly straight cylinder, Ueno et al. [19] reported that an upward gas flow only slightly destabilizes the flow in the liquid bridge, while strong stabilization occurs in the case of a downward gas flow. They made experiments with the Reynolds number of gas up to 100. In the case of a deformed liquid bridge the group of Nishino [20] observed that the upward gas flow destabilizes (stabilizes) the convection in liquid for fat (slender) liquid bridges while the downward gas flow has the opposite effect of the same order of magnitude. The Reynolds number of gas was below 50.

Several numerical [21] and experimental [22,23] studies were devoted to the analysis of an interface deformation in an isothermal liquid bridge caused by gas flow. It was reported that the dynamic deformation is larger when gas enters from above, i.e., parallel to the gravity vector, but the interface deformation does not exceed 10 μm in a millimetric liquid bridge when the velocity of gas is as large as 2 m/s [22]. Given its small magnitude, the free surface deformation is not expected to alter noticeably the stability of flow in liquid. However this statement is controversial because Marangoni stresses may be very sensitive to small perturbations of the interface.

Considering numerically the two-phase model of a non-isothermal liquid bridge, an estimate of the local and average Biot number was proposed based on the heat flux through the interface when gas was moved with different velocities [24] or was enclosed in a large box with a partition block [25,26].

The effects of both interfacial heat transfer and viscous shear acting on the LB surface were considered by Gaponenko et al. [27] and Shevtsova et al. [28] under the conditions of relatively high velocities of the ambient gas flow in liquid bridge filled with 5 cSt silicone oil ($Pr = 68$) and n-decane ($Pr = 12$) in the absence of gravity. In the case when the gas stream comes from the cold side (against the surface flow), a new oscillatory instability was found in the form of an axially traveling wave propagating from the hot to the cold end of the liquid bridge.

The group of Kuhlmann has performed three-dimensional linear stability analysis of a two-phase system (5 cSt silicone oil/argon) when gravity is absent [29]. The stability map, which was presented in terms of critical thermocapillary Reynolds number (analog of the Marangoni number) versus gas velocity, has the form of a maple leaf with a tip on the side of small negative velocities (co-flow with velocity on the free surface). A weak gas stream co-flowing with the thermocapillary surface flow stabilizes the steady basic state while a linearly stable window appears upon the increase of the magnitude of the gas flow. The counter-flow configuration, in general, is more unstable than the co-flow configuration and only fractionally depends on gas velocity.

The two-phase studies mentioned above are associated with the microgravity experiment JEREMI (Japanese European Research Experiment on Marangoni Instabilities) one of whose goals is to study the effect of an external coaxial gas stream on the Marangoni convection in liquid bridges [29]. In the context of this experiment, some preparatory experimental and numerical studies go ahead.

We present experimental and supporting computational study of a two-phase flow in a liquid bridge that develops under the action of buoyant and Marangoni forces in the presence of weak evaporation and a gas stream parallel to the interface. The novelty of the study with respect to closely related research [19,20] is significant and attributed to the innovative design of the set-up. It includes the following issues: (a) the mean temperature of a liquid is kept constant; (b) the temperature of the gas is controlled; (c) the gas temperature varies in a large interval, $10\,^{\circ}C < T_g < 33\,^{\circ}C$; (d) the heat transfer between the lateral sides of the rods and gas is absent. Our analysis highlights two essential points. First, the gas temperature weakly affects the threshold of instability but strongly affects the supercritical flow dynamics. Second, the oscillatory instability can be stabilized by choosing specific temperatures of counter-current gas.

2. Experimental

In order to study hydrothermal instability in the liquid bridge under the action of a parallel gas flow, we have developed a new instrument. The new set-up is profitably different with respect to the previous models as shown in Fig. 1c. In this instrument only the tips of the rods (disk-shaped), which are in contact with liquids, are heated or cooled. The temperature of the disks is adjusted