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The experimental investigation on dynamic response of free surface for non-isothermal liquid bridge with the varying shear airflow

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ABSTRACT

Through high-speed camera and the self-developed software package for interface recognition, the space-time evolution of free surface has been investigated for non-isothermal liquid bridge with shear airflow, and the dynamic response of free surface to the shear airflow has also been analyzed. When the shear airflow is induced from the upper disk ($u < 0$), the convex part of free surface is oppressed downward to the gas side by the shear airflow, which increases the curvature of concave part on the free surface. Under the condition of $u > 0$, the convex part of free surface is pulled upward to the gas side by the shear airflow, which also exacerbates the curvature of concave part on the free surface. The experimental results show that the shear airflow is introduced from upper disk increasing the probability of dam break for the liquid bridge. The deformation of free surface is intensified with the accelerated shear airflow. Due to the different initial free surface shapes (different volume ratios), the direction and intensity of shear stress vary at the different positions of free surface, and the dynamic response law of the free surface deformation is also different. For a liquid bridge with the volume ratio less than 1 ($V = 0.802$, $V = 0.899$), the deformation of free surface presents a certain sinusoidal rule. When the volume ratio of liquid bridge is larger than 1 ($V = 1.071$), under shear airflow induced from upper disk, the deformation of free surface is still presents sinusoidal rule. When the velocity of shear airflow is $u > 0$ ($u = 1$ m/s, $u = 1.5$ m/s, $u = 2.0$ m/s), the convex part of free surface moves up by the lifting action of shear airflow, and the shape of free surface presents multi-peak structure. For the liquid bridge with the large aspect ratio ($\Gamma = 1.4$), the convex region occupies most part of the interface, and there is no change for the free surface shape under the effect of shear airflow. The free surface shape still presents upper concave and lower convex. With the decreasing aspect ratio ($\Gamma = 1.2$), the deformation of free surface is intensified, and the shear airflow can excite obvious fluctuation on the free surface.

1. Introduction

The study on the fluid system with the moving free surface is a challenging problem in modern physics. In the 1850s, the researchers poured much effort into solving the adiabatic or isothermal two-phase flow problems in the fields of crystal growth [1], petrochemical industry, power engineering and refrigeration industry. In recent years, the research on heat and mass transfer for two-phase flow has become a hot topic. In many industrial fields, such as the high quality crystalline semiconductor growth [2], electronic component cooling, and micro-jet flow [3], it has become an important research topic to clarify the heat and mass transfer on the moving gas-liquid interface. Among them, the floating zone method is the main technique for preparing high quality crystal, and the liquid bridge is an important model for numerical simulation and experiment to study on crystal growth process by the floating zone method. It is very important to improve crystal quality by precise study on the thermocapillary convection in crystal growth process and the suppression means. Machida et al. [2] found that the thermocapillary convection is the main reason for exciting micron-size impurity fringes in the crystal growth by floating zone method under microgravity environment. Furtherly, the vibration, magnetic field [4], surface coating [5,6], or shear airflow is conducted in the crystal growth for inhibiting thermocapillary convection. At present, there are many researches focus on the internal flow pattern in liquid bridge, but the study on dynamic deformation of free surface for liquid bridge around the shear airflow is still relatively lack [7,8]. In general, on the boundary condition of free interface, the influence of ambient gas on the thermocapillary convection is discussed by controlling the Nusselt

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number [9]. Shevtsova et al. [10,11], Mialdun et al. [12], Kamotani et al. [13,14], and Ueno et al. [15] found out that the stability of liquid bridge is extremely sensitive to the varing environment conditions in the experiment. There is a dependence relationship between the critical temperature of oscillatory thermocapillary convection and environmental temperature, therefore, the heat conduction and movement of ambient airflow near the free surface of liquid bridge are the important factors which affects the stability of the internal flow structure in the liquid bridge.

In recent years, the influence of ambient airflow on the stability of internal flow in liquid bridge has become a new research direction. Wang, Kamotani and Yoda [16] completed the experiment in different thermotanks for liquid bridge, and confirmed that the critical parameters strongly rely on the temperature of ambient airflow. In the experiments, Kamotani et al. [13] set up the sheet with a temperature around the liquid bridge, and a research is conducted for the effect of sheet heat transfer on the stability of internal flow by changing the relative positions between the sheet and liquid bridge. Irikura et al. [7] investigated influence of the volume flow rate and temperature of shear airflow surrounding the liquid bridge on the onset of oscillatory thermocapillary convection by experiment and numerical stimulation. Tiwari and Nishino [8,17] also extensively carried out research on the similar experiment. Herrada [18], Gaponenko, Mialdun and Shevtsova [19] investigated the effect of isothermal shear airflow on liquid bridge in the annular pools experimental system. The former research is focus on investigating the influence of shear airflow on the internal flow characteristics in the liquid bridge.

As mentioned above, the latest study is focus on the effect of shear flow on the free surface deformation of liquid bridge. They have been preliminary applied in industrial production, such as high quality semiconductor, fiber and micro-jet [20]. However, there are still relatively few studies on the thermocapillary convection in the liquid bridge with the shear airflow, and the experimental data are still lacking.

Melnikov et al. [21] evaluated the influence of the varying Nusselt number on the free surface of liquid bridge with the ambient shear airflow. In addition, the 1cSt silicone oil ($Pr = 18$) as the research object, the effect of heat transfer on the stability of buoyancy-thermocapillarity convection in the three-dimensional liquid bridge with the rigid interface is investigated, and the intensified heat transfer between the gas side and the free surface can effectively change the oscillation characteristic of thermocapillary convection [22]. Miguel et al. [18] used the hexadecane as the medium for simulating the axisymmetric isothermal liquid bridge with the axial shear airflow, and compared the numerical results with the experimental data. It is found that shear airflow can cause the cell flow within the liquid bridge. The surface flow velocity and interface deformation of liquid bridge depend on the shear airflow under the constant gravity and microgravity. When the direction of shear airflow is the same as that of gravity, surface flow is accelerated. While the direction of shear airflow is opposite to that of gravity, the above phenomenon doesn't happen. Matsunaga et al. [23] studied the free surface deformation of 5cSt silicone oil ($Pr = 68$) liquid bridge caused by shear airflow. The shape shifts of free surface deformation were recorded by CCD camera. The research found that the dynamic deformation of free surface mainly depends on the volume ratio and direction of shear airflow. In the plan of Kibo Laboratories Module—JEREMI (Cooperation experiment project by Japanese and European—the study on oscillatory Marangoni convection), this project aims at study on the effect of axial shear airflow on Marangoni convection under microgravity. Shevtsova and Gaponenko [24] proposed numerical simulation for the liquid bridge with the shear airflow under microgravity. Besides, Shevtsova and Gaponenko also conducted numerical and experimental research on gas-liquid two-phase system with the shear airflow under constant gravity [25,19,26] including the study on the perturbation of shear airflow caused by the different structures of liquid bridge [27]. The effect of shear stress and heat transfer by shear airflow on the 5cSt silicone oil liquid bridge is investigated without considering interface deformation under gravity [28]. They found that the thermocapillary convection is accelerated by intensify heat transfer near the free surface, conversely, the thermocapillary convection slows down. At the same time, the ambient shear airflow introduced from the cold disk is more conducive to the heat transfer on the free surface for the liquid bridge. However, a simplified method was adopted to respectively simulate the gas side or liquid side. Yano et al. [29] carried out the instability of non-isothermal liquid bridge with different volume ratios under the shear airflow ($Pr = 28$, $Pr = 67$). Their numerical calculation includes the radiation and convection heat transfer, the research indicates that there is a relationship among the movement of shear airflow, critical Marangoni number (Ma_{cr}), and the volume ratio. Further, Yano et al. set up a mathematical relationship among the Bo number, volume ratio and shear airflow velocity. Yang et al. [30] analyzed numerically the influence of airflow shear on the free surface deformation and the flow structure for large Prandtl number fluid ($Pr = 111.67$) as the parallel airflow shear is induced into the surrounding of liquid bridge from the lower disk or the upper disk. Contrasted with former studies, an improved level set method is adopted to track any tiny deformation of free surface, where the area compensation is carried out to compensate the non-conservation of mass. Present results indicate that the airflow shear can excite flow cells in the isothermal liquid bridge. The airflow shear induced from the upper disk impulses the convex region of free interface as the airflow shear intensity is increased, which may exceed the breaking limit of liquid bridge. The free surface transforms from the “S”-shape into the “M”-shape as the airflow shear induced from the lower disk. For the non-isothermal liquid bridge, the cell flow is dominated by the thermocapillary convection at the hot corner if the airflow shear comes from the hot disk, and another reversed flow cell near the cold disk appears.

As is well known, the instable thermocapillary convection is the main causes of the micron impurities stripe generated in crystal growth. The latest research results show that, three-phase coupling of the free surface deformation, velocity and temperature oscillations at hot corner excites oscillatory thermocapillary convection. The shear stress of shear airflow can effectively interfere free surface deformation and accelerate interface heat transfer. The shear airflow can inhibit the oscillation of thermocapillary convection, furtherly, and improve the quality of crystal. Thus, the study on the interference mechanism of shear airflow to free surface deformation for the liquid bridge has a certain scientific significance.

2. Experimental materials and experimental steps

2.1. Experimental system and physical properties of material

Fig. 1 is a geometric schematic of the experimental device and liquid bridge model, and the dimensioning of experimental device (see the Table. 1) is corresponding to the geometric size in Fig. 1. The liquid bridge is suspended between the two coaxial disks (as shown in Fig. 2). The upper disk is heated and the liquid bridge is surrounded by ambient shear airflow. The shear airflow can be introduced from the upper ($u < 0$) or bottom disk ($u > 0$). The experimental device is applied in the following including the high speed camera equipped with micro focus, liquid bridge generator, plexiglass sleeve, narrow-band filter, magnifying lens, backlight, laser light source (area light), lifting device, inert gas (N2), flowmeter, gas regulator valve, temperature sensor, thermocouple, digital display heating diaphragm, and cooling system. The height of the liquid bridge is h, the radius of coaxial support disk is R_0, the $\Gamma = h/R_0$ represents the aspect ratio of liquid bridge, and the radius of transparent plexiglass sleeve is R_{out}. During the experiment, the R_0 and R_{out} remain unchanged. The 10cSt silicone oil is used as the fluid medium ($Pr = 111.67$) in the experiment. The physical parameters of silicone oil are shown in the Table 2.