Manipulation of Colloidal Droplets in Space and the Instability of Thermocapillary Convection in Large Prandtl Number Liquid Bridge in Microgravity

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Abstract

In 2016 and 2017, SJ-10 and TG-2 satellites were launched. In this short paper, we report recent progress on the studies of manipulation of colloidal droplets and instability of thermocapillary convection in large Prandtl number liquid bridge that based on the space experiments boarding SJ-10 and TG-2 satellites, separately. It was shown that the colloidal droplets can be successfully formed and manipulated in microgravity through the patterned substrates. In another aspect, the coffee ring effect was observed at the first time in space. For the studies of the instability of thermocapillary convection in large Prandtl number liquid bridge in microgravity, our experiments in TG-2 broadened the way of such kind of study and abundant experimental results are emerging.

Key words

Microgravity, Colloidal droplet, Liquid bridge, Thermocapillary convection

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1. Manipulation of Colloidal Droplets in Space

The manipulation of liquid drops under microgravity environment could be very promising in space applications, such as life support systems, wastewater treatment, heat exchangers, machining biologics and pharmacy. Over the past two decades, a variety of microgravity experiments concerning growth and manipulation of liquid drops had been performed. The colloidal self-assembly driven by micro-flow is a un-equilibrium process. The thermal motion of the colloidal particles in the colloidal system is suppressed due to the directional micro-flow which often leads to the macroscopic ordered structure. In microgravity, buoyancy convection was severely suppressed, and there is no hydrostatic pressure, no sedimentation, which provided favorable conditions for in-situ observation of the colloidal self-assembly. “Colloidal ordered assembly and new materials research” is one of the 19 science projects which had been carried out on the SJ-10 satellite. It was the first time to deposit ordered colloidal crystal and study the unequilibrium self-assembly mechanism in space. We performed microgravity experiments of drop manipulation on the SJ-10 satellite and we had successfully conducted drop manipulation experiments in space (see Figure 1). The drop could be captured by a patterned substrate, which was composed of a circular super-hydrophilic matrix surrounded by a super-hydrophobic coating. Through the test of injection, separation, and oscillation of a colloidal drop, it could be shown that this patterned substrate had excellent ability to capture aqueous drops in space. It indicated that the confined drop could be considered as a spherical and ellipsoidal cap model in microgravity and normal gravity, respectively, and the substrate could confine aqueous drops with larger volume under microgravity than in normal gravity. With advantages of simple operation, a strong capacity for

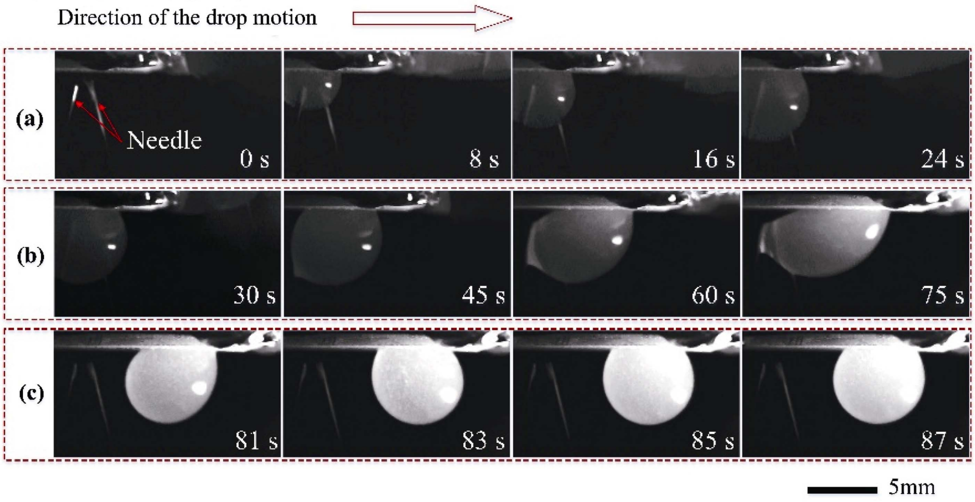

Fig. 1 A large aqueous drop (160 μL) was captured by the patterned substrate in a microgravity environment. (a) Drop injection from the needle. (b) Drop separation from the needle. (c) Drop oscillation and stabilization

capturing large drops in space, this technique showed promising prospects in fluid management, bio-sensing, and pharmacy in microgravity conditions in the future.

We reported a network pattern inside the ring-like stains that form in the final evaporation stage of colloidal droplets (see Figure 2). The previous works might have created an impression that the final pattern morphologies are entirely determined by various microflows inside the droplet. However, in the last stage of evaporation, the pinned droplet will evolve into a thin liquid film, which spontaneously undergoes dewetting and promotes particles inside the coffee ring redistribution to form the resulting patterns. Experimental results show that the evolution of a dry patch could be divided into three stages: rupture initiation, dry patch expansion, and drying of the residual liquid. A growing number of dry patches will repeat these stages to form the network patterns inside the ring-like stain.

Our study expanded the cognition of the "coffee-ring effect".

2. Instability of Thermocapillary Convection in Large Prandtl Number Liquid Bridge

The research focused on the study of the instability of thermocapillary convection in large Prandtl number liquid bridge and to reveal the mechanism of the thermocapillary instability in microgravity (see Figure 3). The study is helpful to give insight into the mechanism of crystal growth in floating zone. This project on TG-2 will make breakthroughs and develop key technologies

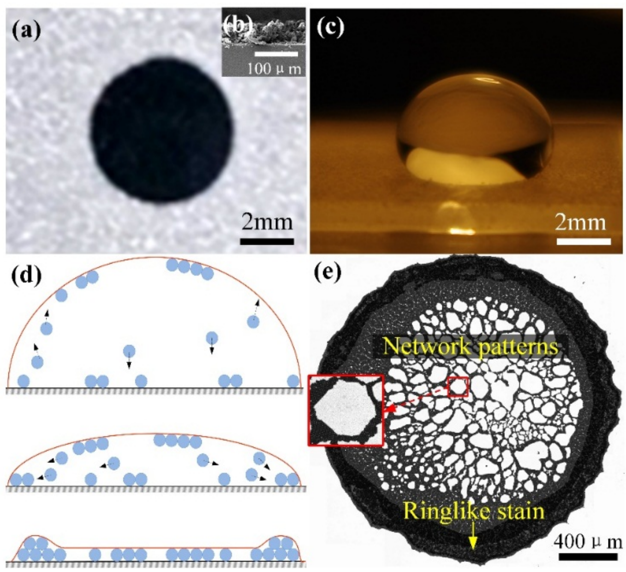

Fig. 2 (a) The tailored substrate is comprised of a circular hydrophilic domain surrounded by a super-hydrophobic coating. The white part is the hydrophobic domain while the black part is the hydrophilic domain. (b) The inset shows SEM image of the cross section of the substrate. (c) A large droplet could be confined in the hydrophilic domain of the substrate. (d) As with evaporation of the colloidal droplet, the self-assembly process of particles is controlled by three kinds of dynamic behavior: Marangoni flow, outward capillary flow, and capillary forces. (e) The network pattern formed inside the ring-like stain, the dry patch in the red rectangle is a typical case that will be emphatically analyzed

(a) slim bridge (b) fat bridge

Fig. 3 Large-scale liquid bridge on TG2

for space experiment, such as the construction, the surface maintenance and the re-establishment of liquid bridge, which further improve the space experiment capability and technical level of microgravity fluid science.

The thermocapillary convections of liquid bridges are experimentally studied in the TG-2 space laboratory. The aspect ratio effect and volume ratio effect on the critical oscillation process in the thermocapillary convection are studied. Based on this, the secondary transition and other problems are discussed.

The payload for thermocapillary convection in the liquid bridge is launched on September 16, 2016 with the TG-2, and the experiment is started on December 3, 2016. The key actions of space experiments such as bridge constructing, bridge pulling, bridge dropping, liquid injection, and liquid absorption were successfully carried out. The thermocapillary convection experiment under different volume ratios and different aspect ratios were successfully completed. Up to now, more than 460 space experiments with different conditions have been completed. Compared with experiments performed in the international space station, this kind of experiments can obtain more abundant results about thermocapillary oscillations.

This space experiment finds novel volume ratio effect whose critical curves have two branches. This effect is extended to the study of aspect ratio, which expands and supplements the classic theory of volumetric effect. For the first time, the critical conditions and oscillations feature of the thermocapillary convection in the liquid bridge is obtained at different Aspect ratios (A_r) and different Volume ratios (V_r). The oscillation in the thin liquid bridge was found to be in low frequency mode, and the oscillation in the fat liquid bridge was in high frequency mode. It is confirmed for the first time that the low-frequency mode is a traveling-wave oscillation mode, the high-frequency mode is a standing-wave oscillation mode, and there is a coupling mode of the traveling wave and the standing wave. The experiment also found a new heating rate effect that the heating rate affects not only the thermal equilibrium relaxation time but also the key parameter selecting the critical oscillation mode (see Figure 4).

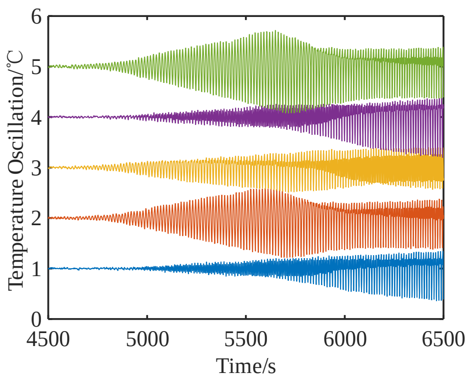

Fig. 4 Temperature oscillation in thermocapillary convection

This project has also obtained abundant thermocapillary oscillation instability and transition phenomena. The typical bifurcation phenomenon, such as double-period bifurcation and quasi-periodic bifurcation, as well as unique new transition routes, such as frequency-stabilized oscillation and frequency periodic jitter, are found. It is found that the low-frequency oscillation mode transits to the high-frequency oscillation mode through the mixed oscillation mode.

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