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A study of the influence of initial liquid volume on the capillary flow in an interior corner under microgravity

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ABSTRACT

In this work the influence of initial liquid volume on the capillary flow in an interior corner is studied systematically by microgravity experiments using the drop tower, under three different conditions: the Concus–Finn condition is satisfied, close to and dissatisfied. The capillary flow is studied by discussing the movement of tip of the meniscus in the corner. Experimental results show that with the increase of initial liquid volume the tip location increases for a given microgravity time, the achievable maximum tip velocity increases and the flow reaches its maximum tip velocity earlier. However, the results for the three different conditions show some difference.

1. Introduction

The equilibrium distribution of fluids and the flow characteristic in a container for the experiments without gravity are very different from those of the ground experiments. Such difference represents a challenge to control the flow of fluids effectively for designing spacecraft systems such as liquid propellants, thermal control systems, wastewater management and recycling system. In the absence of gravity, the capillary forces become the predominant force to influence the fluid orientation. Therefore, it is possible to control the flow and distribution of fluid in spacecraft systems if we have enough knowledge about the capillary forces to be able to predict and master their effects in different containers under microgravity. Scientists have made some efforts on the utilization of capillary forces in fluid management in space. Among these efforts, the study of capillary flow in interior corner has attracted much attention [1–5]. In the application, structures inside tanks providing interior corners are used in the design of fuel tanks so that the fuel will always flow to the outlet of the tank in the absence of gravity [6,7]. So further understanding of capillary flow in an interior corner under microgravity condition is helpful in the design of fluid transport systems on future spacecraft.

The fluid covers the base of the container on the ground because of the dominance of the hydrostatic forces. Upon entering microgravity condition, capillary forces govern the flow and the reorientation of the free surface towards the new equilibrium position often occurs. A mathematical theory proposed by Concus and Finn [8] and later developed by Finn described the equilibrium location of liquid under zero-gravity condition in a container of specified cross-section. According to their theory, the contact angle of the liquid at the interface of the container wall and the geometry of the container determined whether the liquid interface would remain a finite height, with the base still covered with liquid, or move to an infinite height, with the liquid wetting a different portion of the wall. USML-2 Space Shuttle flight experiment conceived and developed by Concus et al. [9] confirmed that this theory could predict the final equilibrium position of the interface in "double proboscis" containers and when the contact angle is smaller than the critical contact angle, no equilibrium configuration is possible, with liquid moving to the walls and rising arbitrarily high along a part of the wall. The related condition that the contact angle is smaller than the critical contact angle is called the Concus–Finn condition. For the container having an interior corner α, the critical contact angle $\gamma_0 = 90^\circ - \alpha/2$. The Concus–Finn condition is satisfied if equilibrium contact angle for the fluid/solid pair $\gamma_s < \gamma_0$, while the Concus–Finn condition is not satisfied if $\gamma_s > \gamma_0$. The capillary flow in the containers with square, equilateral triangular and rectangular cross-sections [1] in the low-gravity environment was studied theoretically and experimentally by Weislogel and Lichter, and the results showed that there are three successive regimes with different meniscus height-time dependences during the capillary flow. The results also displayed the effect of viscosity, container size, corner angle and container aspect ration on the tip location to convey the general character of the capillary flow. However, as a parameter affecting the capillary flow, the influence of initial liquid volume on the capillary flow hasn't been investigated. Furthermore, the theory proposed by Concus and Finn [8] holds that there exists a

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Nomenclature

h	tip location, m	γ_0	critical contact angle, deg
t	microgravity time, s	γ_s	equilibrium contact angle, deg
v	tip velocity, m s^{-1}	η	kinematic viscosity, cSt
V_0	initial liquid volume, mL	ρ	density, kg m^{-3}
		σ	surface tension, N m^{-1}
Greek symbols			
α	interior corner of the container, deg		

significant difference in the capillary flow satisfying and dissatisfying the Concus–Finn condition, and the previous studies are all about satisfying the Concus–Finn condition.

To systematically study the capillary driven flow in an interior corner a series of experiments were carried out in Beijing drop tower, which can provide 3.6 s of microgravity with g-residual estimated at $10^{-5}g_0$ [10,11] All these experiments can be classified into three categories: (1) the contact angle is almost 0, so that it is much smaller than the critical contact angle and the Concus–Finn condition is satisfied, (2) the contact angle is smaller than but close to the critical contact angle and the Concus–Finn condition is still satisfied, and (3) the contact angle is larger than the critical contact angle so that the Concus–Finn condition is not satisfied. We examined the influence of initial liquid volume on the capillary flow in an interior corner in different cases under microgravity. The experimental results showed that the tip location of the meniscus in the corner increased with the increase of the initial liquid volume. The larger initial liquid volume makes the achievable maximum tip velocity larger, and the flow reach its maximum tip velocity earlier. The experimental results are analyzed theoretically and also compared with numerical computations.

2. Experimental setup and procedure

The experimental apparatus is schematically shown in Fig. 1. The main components of the apparatus are a test container made of solid PMMA [poly(methyl methacrylate)], light source and CCD camera. The CCD camera is WAT-660D(CCIR), number of pixels is 537(H) × 597(V) and recording update rate is 25 frame/s. Three types of cross-sections for the test containers are used, including right-angled triangle, isosceles right-angled triangle and rectangle, and the related properties of the containers are listed in Table 1. In this study, we used three different types of test liquids. One of the test liquids is silicone fluids (abbreviated with KF) with a nominal viscosity 5.0cSt. The other two types of liquids are the mixtures of distilled water and ethanol. Since the equilibrium contact angles for distilled water and ethanol on PMMA are 80° and 0°, respectively, the two fluids can be mixed in different proportions to produce a range of contact angles. Therefore, we also used the following two aqueous ethanol mixtures: Eth/H_2O 30/70(% vol.) and Eth/H_2O 40/60 (% vol.). Similar materials have been used by Weislogel and Ross [12] to adjust the contact angles in experiments.

The surface tensions, viscosities and densities of these liquids were measured specifically for this research work using standard laboratory procedures. And the equilibrium contact angles γ_s for each fluid/solid pair were measured by Optical Contact Angle Measuring Device (OCA20) with the SCA-software. The properties of these test liquids are shown in Table 2 with their respective uncertainties. Prior to release of the apparatus into free fall in drop tower, a prescribed amount of fluid is injected into the test container, partly filling it. Upon release, hydrostatic forces are essentially eliminated and the liquid will flow into the corners of the

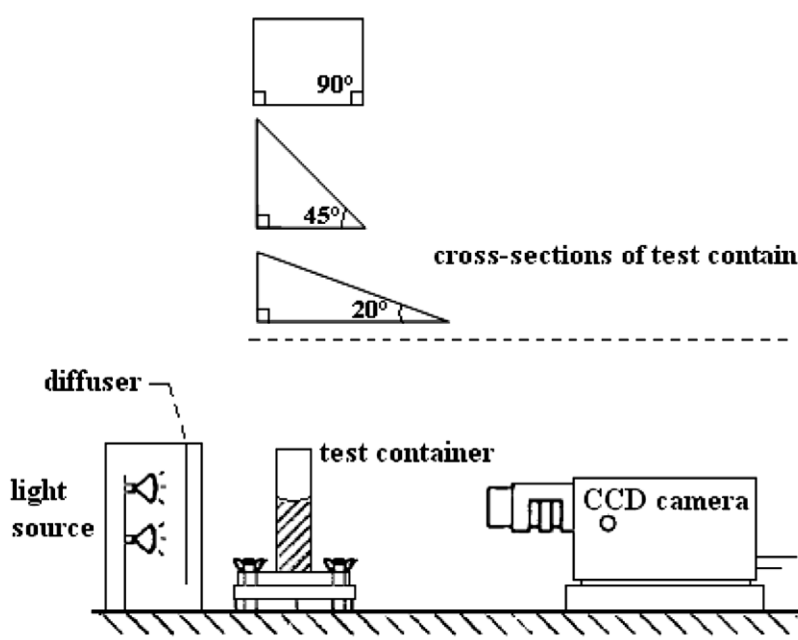
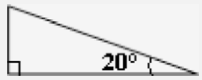
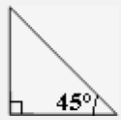
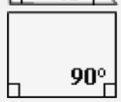


Fig. 1. Schematic of experimental apparatus.

Table 1
Test container data for capillary rise tests.

Container cross-section	Schematic diagram of cross-section	Right-angle side $D_1 \times D_2$ (mm)	Interior corner α (°)	Total height of the container (mm)
Right-angled triangle		33 × 12	20	100
Isosceles right-angled triangle		50 × 50	45	100
Rectangle		45 × 35	90	100

test containers. The progression of the tip location h with microgravity time t was evaluated from the recorded video data.

Because the contact angles are strongly affected by contamination, a procedure for cleaning the test containers is indispensable. Before each experiment, the test containers were rinsed twice with ethanol and cleaned ultrasonically in a warmed detergent for 30 min. After the cleaning, the test containers were again rinsed with the respective test liquid several times and allowed to air dry. Through these cleaning procedures, the surface conditions of the test containers were sufficient to make the resultant data repeatable.

3. Numerical analysis

In this study, a program, named Surface Evolver [13], was applied to determine numerically the equilibrium configuration of liquid in the container. Surface Evolver minimizes the energy of a surface subject to various user-defined constraints by the use of a gradient descent or other minimization methods. A constraint can be a quantity integrated over a surface, or it can be a quantity constant such as a volume. A constraint can also be a geometric constraint such as a wall through which the surface is not to penetrate. For the zero-gravity interface in this study, the energy includes only the interfacial energy between the liquid and the solid wall. Without gravity or accelerations, the problem is a geometrical problem with results determined by shape, α, and equilibrium contact angle γ_s.

When the liquid in the container with interior corner satisfies the Concus–Finn condition ($\gamma_s + \alpha/2 < 90°$), the surface is either unbounded in ground or fails to exist in microgravity and the numerical results show the unconverged surfaces. When the liquid in the container with interior corner does not satisfy the Concus–Finn condition ($\gamma_s + \alpha/2 > 90°$), an equilibrium configuration of liquid exists both in ground and in microgravity [14].

Table 2
Relevant fluid/interfacial properties.

	$\sigma \pm 5\%$ (N m^{-1})	$\rho \pm 5\%$ (kg m^{-3})	$\eta \pm 1\%$ (cSt)	$\gamma_s \pm 2°$ (°)
KF96-5	0.0197	915	5.0	0
Eth/H_2O 40/60 (% vol.)	0.0328	916	2.11	42
Eth/H_2O 30/70 (% vol.)	0.0364	937	1.83	54

Table 3
Cases tested with surface evolver.

Case	α (°)	γ_s (°)
1	20	0
2	45	42
3	90	54

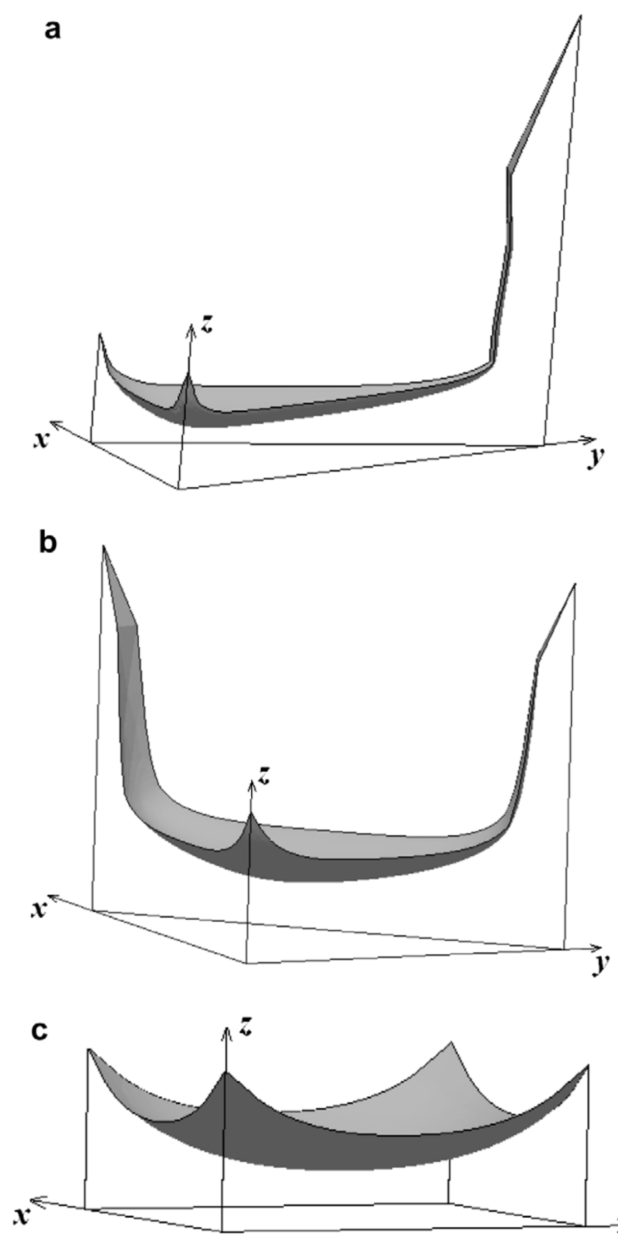


Fig. 2. Unconverged surface and equilibrium surface in the surface evolver simulation: (a) unconverged surface: $\gamma_s = 0°$, $\alpha = 20°$; (b) unconverged surface: $\gamma_s = 42°$, $\alpha = 45°$; (c) equilibrium surface: $\gamma_s = 54°$, $\alpha = 90°$.

In this study, three typical cases are computed with the parameters listed in Table 3. For each case computed, the iteration of Surface Evolver starts with a coarse grid of nominally 1024 (2^{10}) facets. With necessary refinement, the number of facets increases to up to approximately 16,384 (2^{14}). For the given conditions, the equilibrium surface or the unconverged surfaces of the three cases are shown in Fig. 2. Fig. 2(a) and (b) show the unconverged surfaces of liquid in right-angled triangle and isosceles right-angled triangle test containers in microgravity. Fig. 2(c) shows the equilibrium surface of liquid in rectangle test container in microgravity. The numerical results also show that the initial liquid volume has no effect on the equilibrium configuration of liquid.

4. Results and discussions

With the release of the drop capsule, a microgravity condition was established and the liquid in the container climbed at the interior corners. The images could be obtained by CCD camera at different time after entering microgravity condition, and the images for the three cases at the end of 3.6s microgravity are shown in Figs. 3–5.

Through analyzing the images, data of a series of progression of tip location vs. microgravity time (h–t) and tip velocity ($\Delta h/\Delta t$) vs. microgravity time (v–t) were achieved, as shown in Figs. 6–8.

Figs. 6–8 show typical experimental results of the effect of initial liquid volume on the capillary driven flow under microgravity conditions, where tip location h and tip velocity v, corresponding to different interior corners: 20°, 45°, 90°, respectively, are plotted vs. microgravity time t. They represent three different conditions of capillary flow: cases (1)–(3) as above mentioned.

For the case of static contact angle $\gamma_s = 0°$ (Fig. 6), as an extreme case satisfying the Concus–Finn condition, the tip velocity in interior corner is very large. When the Concus–Finn condition is satisfied, there exists a thin column of liquid in the corner prior to the drop test [8] which makes the true tip location of the meniscus ambiguous during the early stage of the drop tests. So an apparent tip location was measured at the beginning of the flow by extrapolating the apparently linear meniscus profile near the tip to the vertex of the corner in the concrete operation. Similar method has been used by Weislogel and Lichter [1] in experiments. In microgravity the liquid in the container moves to the interior corners and can rise arbitrarily high along interior corner, uncovering a portion of the base if the container is tall enough. The flow enters the velocity decreasing stage very rapidly. Quickly rising of the liquid at the initial stage reduces the amount of the liquid left on the base of the container significantly, which leads to the slow decreasing of tip velocity following the rapid decreasing.

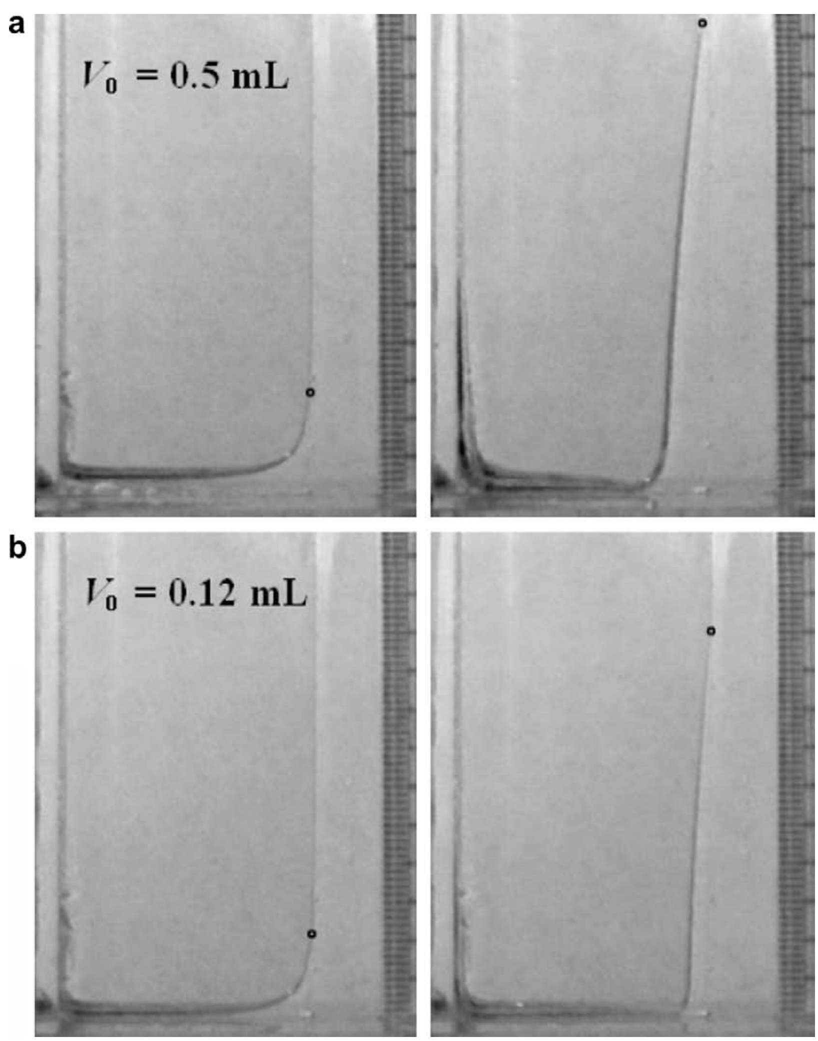


Fig. 3. Typical image of the flow at different microgravity time: (a) V_0 = 0.5 mL, (b) V_0 = 0.12 mL. Left: t = 0 s, right: t = 3.0 s. Test liquid: KF96-5, $\gamma_s = 0°$, $\alpha = 20°$ (the circle denotes the tip location of the meniscus in the corner).

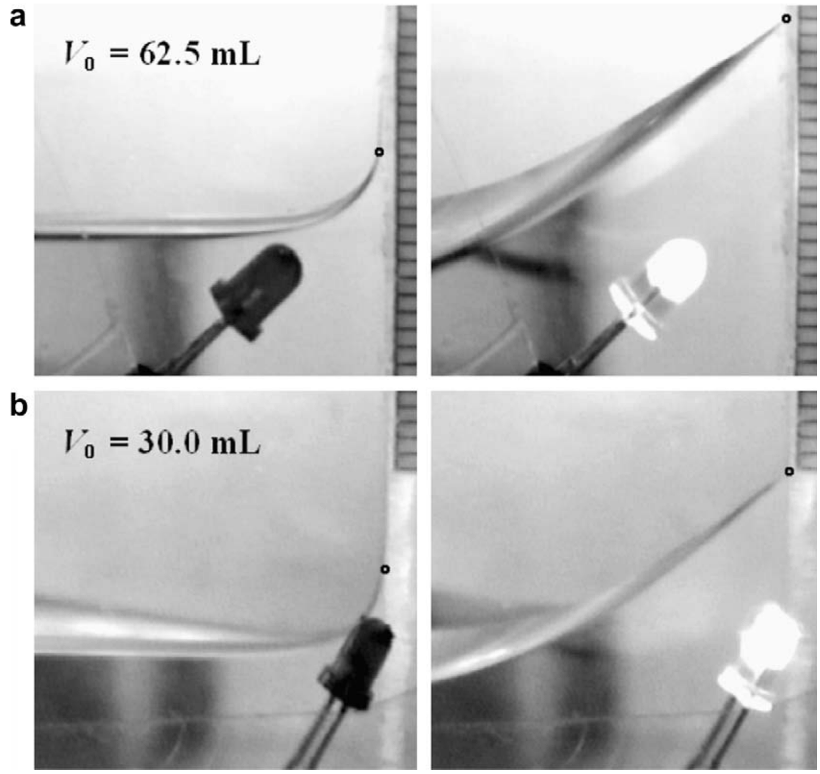


Fig. 4. Typical image of the flow at different microgravity time: (a) V_0 = 62.5 mL, (b) V_0 = 30.0 mL. Left: t = 0 s, right: t = 3.6 s. Test liquid: Eth/H_2O 40/60(% vol.), $\gamma_s = 42°$, $\alpha = 45°$ (the circle denotes the tip location of the meniscus in the corner).

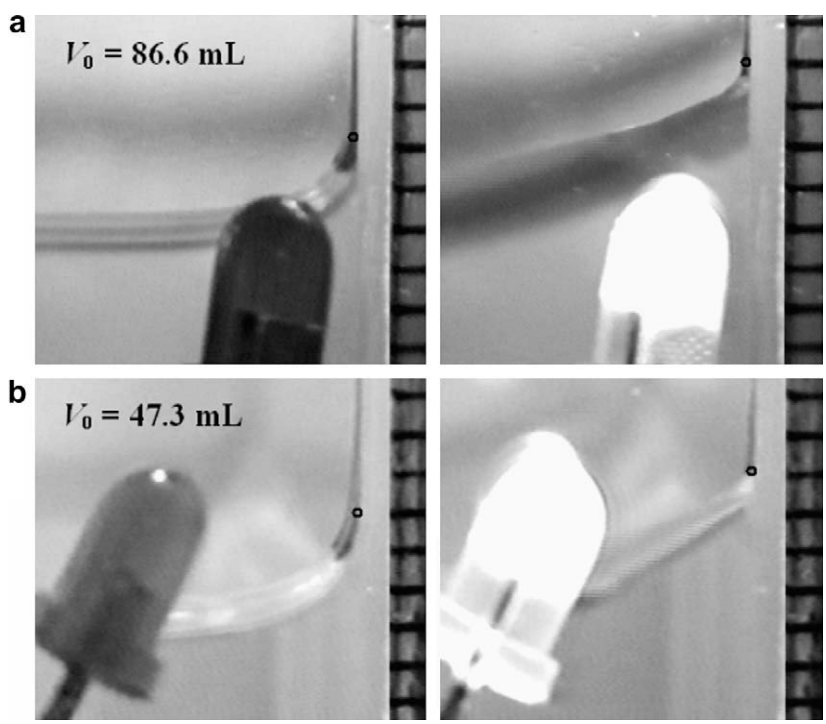


Fig. 5. Typical image of the flow at different microgravity time: (a) V_0 = 86.6 mL, (b) V_0 = 47.3 mL. Left: t = 0 s, right: t = 3.6 s. Test liquid: Eth/H_2O 30/70(% vol.), $\gamma_s = 54°$, $\alpha = 90°$ (the circle denotes the tip location of the meniscus in the corner).

For the case of static contact angle $\gamma_s = 42°$ (Fig. 7), as a general case close to and satisfying he Concus–Finn condition, the tip velocity is much lower than the case of $\gamma_s = 0°$, as shown in Figs. 6 and 7(b). On this condition the measured tip location was still apparent tip location. In the stage of the velocity decreasing, the lower tip velocity leads to more liquid in the base of the container comparing to Fig. 6(b) and less influence by the no-slip boundary condition. During the later period of velocity decreasing the tip moves at a constant

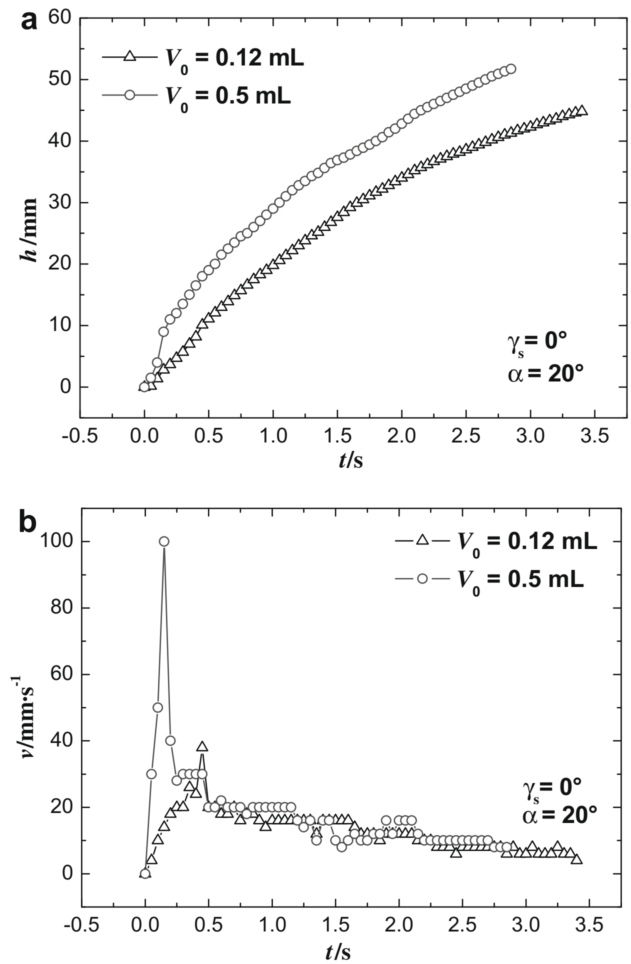


Fig. 6. The tip location h (mm) and tip velocity v (mm s^{-1}) as a function of microgravity time t(s) in right-angled triangle test containers for different initial volume (V_0). Test liquid: KF96-5. The reference point (coordinate origin) is the tip location of meniscus in corner under gravity condition.

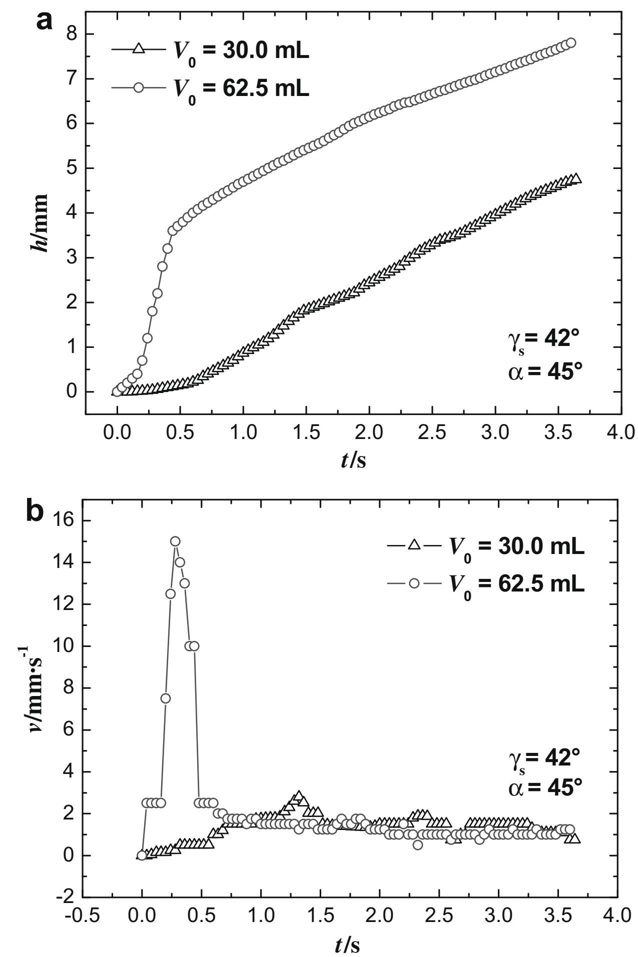


Fig. 7. The tip location h (mm) and tip velocity v (mm s^{-1}) as a function of microgravity time t (s) in isosceles right-angled triangle test containers for different initial volume (V_0). Test liquid: Eth/H_2O 40/60 (% vol.). The reference point (coordinate origin) is the tip location of meniscus in corner under gravity condition.

speed for a certain period of time regardless of the initial liquid volume, which might be helpful for steadily transporting liquid in space.

For the case of static contact angle $\gamma_s = 54°$ (Fig. 8), as a general case dissatisfying the Concus–Finn condition, there exists an equilibrium configuration of liquid covering the base of the container simply. On this condition, the liquid will flow at the interior corner and the measured tip location is true tip location. According the above computational results of Surface Evolver, the initial liquid volume has no effect on the equilibrium configuration of liquid. The tip velocity will reduce to zero when the equilibrium configuration of liquid is reached. Considering the experimental results that the tip velocity with larger initial volume is larger as shown in Fig. 8, the liquid should reach the equilibrium configuration earlier. Therefore, the tendency of h–t after 3.6 s microgravity time can also be predicted by combing the numerical and experimental results. In Fig. 8, since the tip velocity is quite low, the change of the tip location for one frame update is very small. To measure more observable change of the tip locations, the data points were taken after passing several frames.

From Figs. 6–8 it can be seen that for three different conditions there always exists maximum tip velocity which connects two successive stages: the velocity increasing stages and the velocity decreasing stages. The results show that the tip location always increases with the increase in initial liquid volume. The larger initial liquid volume will make the achievable maximum tip velocity increase and make the flow reach its maximum tip velocity earlier.

The above experimental results that the tip velocity differs with the liquid initial volume can be briefly explained by no-slip boundary condition. A moving liquid in contact with a solid body is supposed to have no velocity to the body at the contact surface. The condition of not slipping over a solid surface has to be satisfied by a moving liquid, which is known as the no-slip boundary condition. At the initial stage of the velocity increasing, the inertia force is dominant and the tip velocity increases with the increase in the initial liquid volume. When entering the velocity decreasing stage, the flow is controlled by friction force and the no-slip boundary condition plays a leading role. The liquid in the bottom of the container should satisfy the no-slip boundary condition, so there exists a velocity distribution in vertical direction. The thinner the liquid layer is, the bigger the resistance. The tip velocity in interior corner becomes slower.

5. Conclusions

The capillary flow in interior corners for three different conditions is studied experimentally under microgravity using a 3.6 s drop tower. The experimental results showed that with the increase of initial liquid volume the tip location increases for a given microgravity time, the achievable maximum tip velocity increases and the flow reaches its maximum tip velocity earlier. In addition, for the case that the contact angle is smaller than but close to the

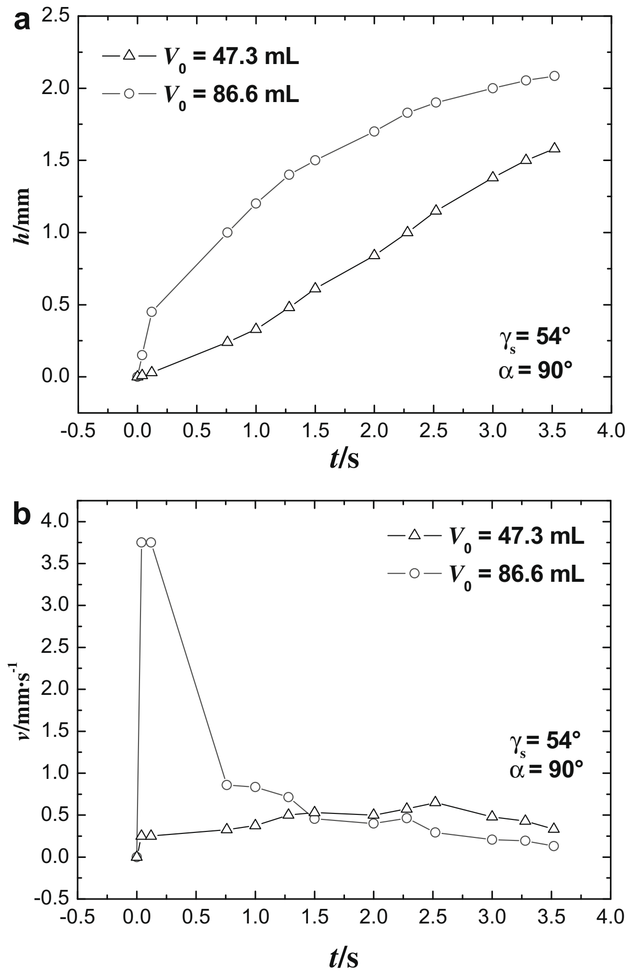


Fig. 8. The tip location h (mm) and tip velocity v (mm s^{-1}) as a function of microgravity time t (s) in rectangle test containers for different initial volume (V_0). Test liquid: Eth/H_2O 30/70 (% vol.). The reference point (coordinate origin) is the tip location of meniscus in corner under gravity condition.

critical contact angle, preliminary experimental results showed that there exists constant speed of tip flow for a certain period of time regardless of the initial liquid volume. The results in this study may be useful for controlling the transportation of liquid under microgravity.

Acknowledgments

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