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Influence of Contact Angle and Tube Size on Capillary-Driven Flow Under Microgravity

Caixia Wang, Shenghua Xu, Zhiwei Sun,* and Wenrui Hu
Chinese Academy of Sciences, 100190 Beijing, People's Republic of China

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The influence of contact angle and tube radius on the capillary-driven flow for circular cylindrical tubes is studied systematically by microgravity experiments using the drop tower. Experimental results show that the velocity of the capillary flow decreases monotonically with an increase in the contact angle. However, the time-evolution of the velocity of the capillary flow is different for different sized tubes. At the beginning of the microgravity period, the capillary flow in a thinner tube moves faster than that in a thicker tube, and then the latter overtakes the former. Therefore, there is an intersection between the curves of meniscus velocity vs microgravity time for two differently sized tubes. In addition, for two given sized tubes this intersection is delayed when the contact angle increases. The experimental results are analyzed theoretically and also supported by numerical computations.

Nomenclature

a = the distance between the wetting barriers, mm
c = the radius of the centerline of the free surface inside the reservoir, mm
d = internal diameter of tube, mm
h = meniscus height, mm
$\dot{h}$ = meniscus velocity, m/s
$\ddot{h}$ = meniscus acceleration, $\mathrm{m/s^2}$
h_0 = initial liquid height, mm
R = internal radius of tube, mm
Rc = the radius of the free surface inside the container, mm
t = time, s
t_r = the reorientation time, second
γ_d = dynamic contact angle, deg
γ_s = static contact angle, deg
ν = kinematic viscosity, cSt
ρ = liquid density, $\mathrm{kg/m^3}$
σ = surface tension, N/m

I. Introduction

THE capillary-driven flow has long been investigated by scientists and engineers [1–3] both theoretically and experimentally, because of its importance for fluid dynamics, surface science, and especially for fluid management in space. In earlier years, most relevant experiments were performed under normal gravity conditions [4,5]. However, the capillary-driven flow becomes remarkable only when the size of the capillary tube is small for terrestrial experiments. To solve this problem, many researchers recently began to experimentally study the capillary-driven flow under microgravity because large sized capillary tubes can be used by removing the effect of gravity. Related theories are also progressing. Levine et al. [6] made modifications to the Lucas–Washburn equation [1,2] by introducing the appropriate momentum balance equations and presented the most detailed theory for the capillary rise in tubes. Dreyer et al. [7] examined the capillary-driven flow under microgravity in a 4.7 s drop tower using parallel plate channels, and the results showed that at an early stage of penetration, the capillary rise is governed by inertial forces. Weislogel and Lichter [8] studied the capillary-driven flow along the interior corners of a partly filled container in microgravity using a 2.2 s drop tower and modified *h-t* (rising height vs time) dependencies were observed. Chen and Collicott [9] presented the experimental results on capillary flow in a vane-wall gap geometry obtained with the Purdue drop tower, and effects of geometric parameters, contact angle, and the fluid viscosity on the flow were investigated. An experimental study on the capillary-driven flow and the final equilibrium position of the interface in double proboscis containers conceived and developed by Concus et al. [10] was carried out by the USML-2 space shuttle flight. For circular cylinders, the capillary rise flow was extensively studied by Stange et al. [11] and typical three-flow regimes were identified with the aid of analytical and experimental results. Dreyer has included some recent progress in the study of capillary flow under microgravity in his book [12].

Because of removal of the ubiquitous effects of gravity in terrestrial experiments on fluid behavior, experiments in microgravity make it possible to deepen our knowledge of the nature of capillary-driven flow. This knowledge is particularly important for the design of fluid transfer systems of spacecraft, such as propellant and cryogenic fluid tanks, thermal control systems, coolant reservoirs, and systems for collection, storage, and provision of water [13]. It is also helpful in improving modeling studies predicting fluid flows in porous media [14,15]. Under microgravity conditions, the flow behavior of fluid is rather complicated due to the competition of different influencing factors, including contact angle, tube size, and so forth. However, there is still a lack of systematic study on the effects of these factors on the dynamic of capillary-driven flow.

In this study we performed a series of experiments in a Beijing drop tower, which provided 3.6 s of microgravity, to systematically study the influence of contact angle and tube radius on the capillary-driven flow under microgravity. As a basic model of fluid transfer systems, circular cylindrical tubes are adopted in the experiments. The results show that the larger contact angle will decrease the velocity of the capillary flow. We found, however, that the time evolvements of the velocity of the capillary flow are different for different sized tubes. At the beginning of the microgravity period, the capillary flow in a thinner tube moves faster than in a thicker one, and then the latter overtakes and outstrips the former. Therefore, there is an intersection between the curves of meniscus velocity vs microgravity time for two different sized tubes. In addition, for two given sized tubes this intersection delays when the contact angle becomes larger. The experimental results are analyzed theoretically and also supported by relevant numerical computations.

II. Experimental Setup and Procedure

A cylindrical acrylic container with internal diameter 150 mm and total height 150 mm was used for the experiments. The container was

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*Key Laboratory of Microgravity, National Microgravity Laboratory, Institute of Mechanics; sunzw@imech.ac.cn.