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Study of the quasi-static motion of a droplet expelled from a pipe in microgravity

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ABSTRACT

In this paper, a theoretical and numerical study of the quasi-static motion of a large droplet pushed out of a pipe in microgravity environment was presented. For the existence of surface force, an external force is needed to push the droplet out of the pipe. Methods to calculate the external force, the surface force, and the pressure drops were established in theoretical model and numerical simulation, respectively. The changes of the free energy, the surface force, as well as the pressure drops during a droplet being pushed out of a pipe were discussed in this work. The surface force reaches its maximal value, when the radii of upside contact line equals to the radius of the pipe. At last, a comparison of the two methods was made based on the results.

1. Introduction

The effects of surface force and capillary action play a dominant role in space fluid management, and its mechanism is used in many fields in the aerospace engineering, for example, the thermal control components on spacecraft [1,2], liquid droplets radiator for the high-power space systems [3,4], free-drop techniques for the engine ignition on satellites [5], as well as the evaporation and combustion of droplets in the rocket engine [6]. However, in these systems, surface force may have negative effects. For instance, droplets being absorbed into the vent pipe of the tank, which could result in the discontinuity of the fuel transfer. And it is difficult to push the droplets out of the pipe. As the result, it is crucial to have a good understanding of the process of a droplet being pushed out from a pipe in microgravity.

In space, capillary forces and surface tension turn out to be the major mechanism driving the droplets through a channel or a pipe in the absence of gravity. It makes the movement of the droplets in pipes in space, similar to the movement of the droplets in capillaries on the ground, for little difference in the value of Bond number [7]. By now, a large number of studies on the performance of liquids in a capillary on the ground have been carried out. Lucas and Washburn, who made the first rigorous analysis of the dynamics of capillary flow, neglected inertia in their analysis [8,9]. The dynamics of capillary flow also depends on many other factors such as inertia, dynamic contact angle, fluid rheology, and even shape variation of the channel, which are addressed in many literatures [10–13]. In these studies, the droplet shape techniques, based on the shape of a droplet for surface force measurement were developed [14,15]. Some results or methods of these studies are helpful to the space droplets movement research.

In this paper, a theoretical and numerical study of a hydrophilic droplet pushed out of an axisymmetric and smooth pipe was presented. The analysis in this work was restricted to quasi-steady movement, which means the velocity of the droplet in the pipe is nearly zero and the droplet remains equilibrium for all positions. Consequently, all dynamic aspects are neglected, the model here, involves only the free energy of the internal interfaces of

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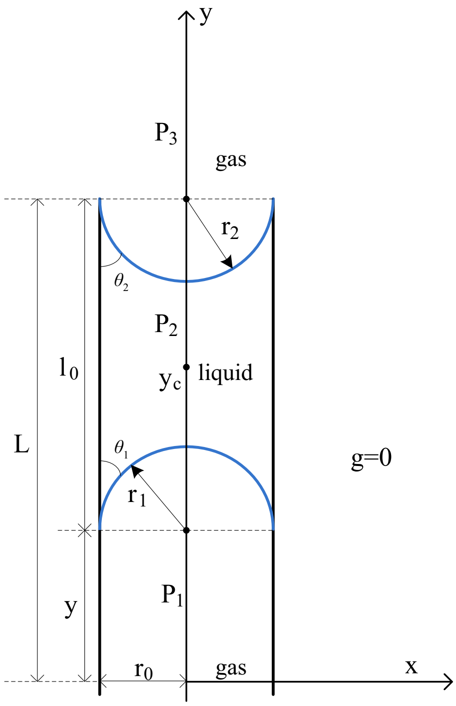

Fig. 1. Sketch of a droplet in a pipe.

the system and external pressures [16,20]. Thus, only geometry related effects were considered. With these assumptions and simplifications, the minimum forces or pressures needed to push a droplet through the system can be calculated accurately.

2. Description of the physical model

As shown in Fig. 1, the system considered here, is a large droplet with a fixed volume V in a hydrophilic pipe of length L. The pipe is filled with a gas, and the large droplet is clogged in the pipe. By large we mean that the volume V of the droplet is larger than $\frac{4}{3}\pi r_0^3$. The large droplet divides the gas into two disconnected parts. The pipe is smooth and axisymmetric about the y axis with a radius r_0, thickness of the wall of the pipe is neglected. The droplet itself consists of a bulk part in direct contact with the walls of the pipe and of two menisci, in contact with the gas, capping the ends of the droplet. The upside menisci is contacted with the gas outside of the pipe. In the space environment, the gravity can be neglected, which ensures that the menisci can be approximated by spherical caps [14].

A coordinate is chosen and y is the coordinate of the lowest point in the underside menisci, changing with the movement of the droplet. The quasi-static equilibrium assumption makes it relatively simple to combine mass conservation with geometric constraints to determine, as a function of the droplet position, the pressure drops over the two menisci needed to maintain this equilibrium.

2.1. The external force

Base on the quasi-steady assumption, the Newtonian equation of motion can be written as:

$$F_{ex} - F_{st} = 0 \tag{1}$$

where, F_{ex} is the external force to push the droplet out, F_{st} is the sum of the surface force caused by geometry change of the droplet.

Here, the surface force is the resistance to balance the external force. Such resistance can be calculated by using the surface free energy method. Generally, the surface force is regarded as the sum of the surface tension acting on per unit length of the interfacial contact line, which equal to the surface free energy based on per unit interfacial area. As shown in Fig. 1, the total surface Gibbs free energy of the system is expressed as

$$G_{tot} = \sum_i \sigma_i A_i = \sigma_{\lg} A_{\lg} + \sigma_{sg} A_{sg} + \sigma_{sl} A_{sl} \tag{2}$$

Where $\sigma_{\lg}$, σ_{sg}, σ_{sl} are the surface free energy of the liquid–gas interface, the solid–gas interface, the solid–liquid interface, respectively. $A_{\lg}$, A_{sg}, A_{sl} are the surface areas of the liquid–gas interface, the solid–gas interface, the solid–liquid interface, respectively. The sum of the surface force F_{st} is given by the gradient of the total internal energy with respect to the coordinate of the droplet y. Hence

$$F_{st} = \frac{dG_{tot}}{dy} \tag{3}$$

which depends on the droplet position y and, through the areas A_i. Thus the external force F_{ex} can be calculated from Eq. (1).

2.2. The pressure drop

To maintain a curved interface between the gas pressure and the liquid pressure, the pressure drop must obey the Young–Laplace equation [17]:

$$\Delta P = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = 2\sigma \frac{\cos\,\theta}{r} \tag{4}$$

where R_1 and R_2 is the main radii of curvature of the curved interface between the gas and the liquid. In this paper, the interface is axisymmetric about the y axis, $R_1 = R_2$. θ is the contact angle.

From Fig. 1, to maintain the droplet being in quasi-static equilibrium, the pressure drop between the lower menisci must be:

$$\Delta P_1 = P_1 - P_2 = 2\sigma \frac{\cos\,\theta_1}{r_1} \tag{5}$$

And the pressure difference between the upper interface can be obtained:

$$\Delta P_2 = P_3 - P_2 = 2\sigma \frac{\cos\,\theta_2}{r_2} \tag{6}$$

The total pressure drop ΔP over the droplet system is:

$$\Delta P = P_1 - P_3 = \Delta P_1 - \Delta P_2 = 2\sigma\left(\frac{\cos\,\theta_1}{r_1} - \frac{\cos\,\theta_2}{r_2}\right) \tag{7}$$