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Capillary flow rate limitation in asymmetry open channel

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Abstract This paper focuses on the stability of capillary forced flow. In space, open capillary channels are widely used as the liquid and gas separation devices to manage liquid positioning and transportation. Surface collapse happens when the flow rate exceeds the critical value, leading to a failure of propellant management. Knowledge of flow rate limitation is of great significance in design and optimization of propellant management devices (PMDs). However, the capillary flow rate limitation in an asymmetry channel has not been studied yet in the literature. In this paper, by introducing an equivalent angle to convert the asymmetry corner to a symmetry one, the one-dimensional theoretical model is developed. The flow rate limitation can then be investigated as a function of the channel geometry as well as liquid property based on the model. Comparisons between the asymmetry and symmetry channels bring forth the characteristics of the two kinds of channels, and demonstrate good accordance between the new advanced model and the existing one in the literature. This theoretical model can provide valuable reference for PMD designers.

1. Introduction

As the most widely used devices for gas and liquid separation in space, capillary channels mainly control liquid and gas locations by surface tension, the primary force dominating liquid behavior in microgravity. In surface tension tanks of satellites, propellant management devices (PMDs) use capillary channels to manage propellant, keeping the gas from ingesting into the liquid. Moreover, capillary channels are critical to many important fluids management systems such as fuels' storage systems, life support systems and other materials processing in the liquid state.[1–6]

In surface tension dominated systems, when liquid is drained from channels, it forms a curving free surface in the open side of the channel to balance the pressure difference between the liquid and the surrounding gas. The liquid pressure decreases along the flow direction due to the convective and viscous momentum transport. Increasing the flow rate causes larger pressure loss. The collapse of the free surface will happen when flow rate exceeds the critical value and then the capillary pressure can no longer balance the pressure difference. Surface collapse and gas ingestion lead to a failure of propellant management. The investigation of capillary surface

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collapse is not only a problem deserving scientific research but also of practical significance in PMD engineering field.

Capillary flow rate limitation has been studied extensively since the 1960s. Literature has focused on different types of channels as PMDs usually appear in different geometries. Fundamental work of the capillary flow rate limitation problem has been done theoretically, numerically and experimentally.[7–9] To cite a few, Rosendahl et al.[10] established the one-dimensional model for parallel channels neglecting the curvature in flow direction. In succession, Haake et al.[11,12] and Grah et al.[13] expanded the theory to groove channel geometries. In the 1990s, the United States performed a series of fluid acquisition and resupply experiments in space to test the ability of vane surface tension tanks, such as FARE (fluid acquisition and resupply experiment) II and VTRE (vented tank resupply experiment).[14,15] Tanks consisting of inner vanes mounted to a central standpipe as well as outer vanes following the profile of the tank wall (see Fig. 1) demonstrated good capability in liquid management. As sketched in Fig. 1, inner vanes formed the wedge-shaped interior corners in the central while outer vanes and the tank wall constituted the asymmetry interior corners formed by one straight side and one arc. Klatte[5] and Wei et al.[16,17] have studied the surface collapse behavior of wedge-shaped channels theoretically and experimentally. For this asymmetry corner, Weislogel and Collicott[18] investigated the capillary rewetting phenomenon by approximating the curved portion with a straight section and then improved the precision by approximating the corner with an isosceles triangle. However, this approximation is only appropriate when the number of outer vanes is large. So far, for the asymmetry channels, due to its complexity in geometry, the surface collapse behavior and flow rate limitation have not been considered in the literature.

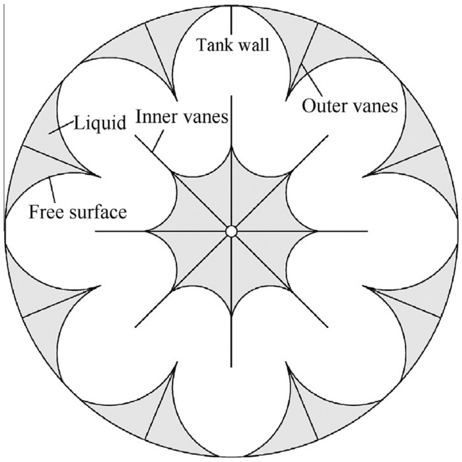

Fig. 1 Schematic of tank cross-section.

This paper focuses on the flow stability in asymmetry channels. We aim to determine the critical flow rate that leads to the surface collapse. Despite that the general capillary equations are universal for various channel geometries, pressure loss is different. That's why authors have studied the problem from one channel geometry to another in the literature. The asymmetry peculiarity adds complexity to modeling and analysis. To reduce the complexity, we introduce a geometrical method to convert the asymmetry corner to an equivalent symmetric one according to the work of Li et al.[19,20] Based on the equivalent corner, the one-dimensional flow model is established. The flow rate limitation can then be determined by numerical solution of the governing equation system and validated by CFD simulation. Surface curvature and pressure loss are analyzed in detail to comprehensively understand the surface collapse mechanism.

2. Model for asymmetry channel

2.1. Flow model

The asymmetry channel we consider is shown in Fig. 2. The channel is of vane width d, tank radius r and channel length l. On the open side it forms a free surface when the liquid flows along the x-axis from the inlet to the outlet. The flow is maintained by an external pump with flow rate Q at the outlet, imitating the draining process of the satellite tank in space. The channel is surrounded by passive atmosphere of constant pressure p_a. Liquid flow is considered to be laminar, isothermal and incompressible. It is assumed that the velocities along y and z directions are neglectable compared with that in x direction and the cross-section changes sufficiently small. Hence the flow can be considered as one-dimensional along x-axis. Liquid constant properties are the kinematic viscosity υ, surface tension σ and density ρ. The liquid wets the channel with a constant contact angle γ, neglecting any contact angle hysteresis. Coordinate system is located at the bottom of the inlet.

As the symmetry of vanes and wall in a surface tension tank, the surface may be determined by analyzing the smallest symmetrical element sketched in Fig. 3. For this corner, it is not easy to find proper parameters to describe the surface since it is asymmetric. Thus a geometric method of structuring an equivalent corner[19] is introduced in the following way. A tangent line is drawn at the contact location C and intersects with the extension line of $\overline{AO}$, forming the equivalent corner $\angle O'$. Confined by the contact condition, this dummy interior corner shares the same surface with the actual asymmetry one. We model the flow based on the equivalent corner as it is of wedge

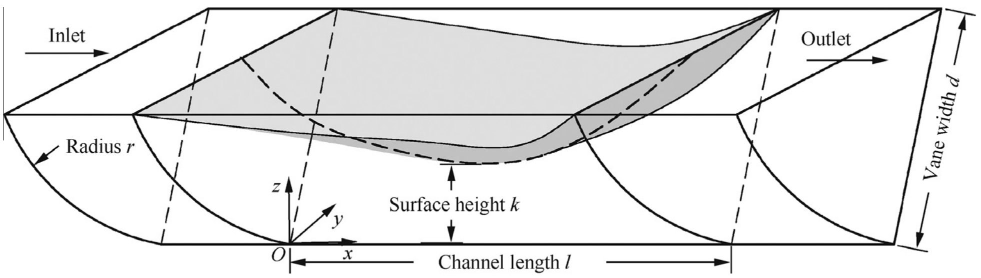

Fig. 2 Schematic of asymmetry channel.