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The Review of the Interior Corner Flow Research in Microgravity

Jinghao Li\textsuperscript{a,}\textsuperscript{b*}, Xiaoqian Chen\textsuperscript{a}, Yiyong Huang\textsuperscript{a}

\textsuperscript{a}College of Aerospace and Material Engineering, National University of Defense Technology, Changsha 410073
\textsuperscript{b}People’s Liberation Army 91 Subunit 91550 Unit, Dalian 116000

Abstract

In this paper the theoretical research of vane-type surface tension tank and the study of the interior corner flow are reviewed. Firstly, the conception of interior corner flow and its application in the research of vane-type surface tension tank are introduced. Then the development of analytical solutions about the interior corner flow is expounded, besides some important numerical solutions and experiments in microgravity condition. Up to now, a great deal researches of interior corner flow are carried out overseas, including many drop tower experiments and some space experiments. This paper will provide valuable references for the surface tension tank and interior corner flow research.

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1. Introduction

By the progress of satellite and on orbit servicing (OOS), more and more satellites are using vane-type surface tension tank. Vane-type surface tension tank can not only supply propellant to satellite engine, but also used in on orbit refueling (OOR) to manage the propellant filling. The principle of the vane-type surface tension tank is the capillary-driven flow along interior corner which is formed by two vanes.

*Corresponding author. Tel: +86-13755069504. E-mail address: jinghao0728@hotmail.com.
The research of interior corner flow begins at 1960s, and mainly studies the capillary-driven flow in the V-shaped corner region with mathematical solutions. It is not an easy work, and furthermore in the initial stage of the research, the microgravity experiment condition is not mature. So there are not many successes about interior corner flow up to 1990s. In recent years, the research of on orbit refueling is developed quickly and the vane-type surface tension tank is widely used. Accordingly, the interior corner flow attracts attention again, and makes great progress in theoretical research and also takes many drop tower experiments and several space experiments. This paper introduces the progress of theoretical research about interior corner flow and correlative experiments in microgravity condition.

### Nomenclature

| Symbol | Description               |
|--------|---------------------------|
| \( \theta \) | contact (wetting) angle |
| \( \alpha \) | corner half-angle         |
| \( \delta \) | surface curvature angle, \( \pi/2 - \alpha - \theta \) |
| \( f \) | surface curvature function |
| \( R \) | radius of curvature       |
| \( h \) | meniscus height from z-axis |
| \( S \) | parameterized surface elevation |
| \( L \) | length of meniscus        |
| \( \varepsilon \) | fluid column slenderness ratio, \( h / L \) |

### 2. Concus-Finn condition

In 1969, Paul Concus and Robert Finn [1,2] addressed the criterion for when large scale flows occur in corners. They show that capillary-driven flows in corners of infinite extent proceed to infinite distances when the condition \( \theta < \pi/2 - \alpha \) is satisfied, hereafter referred to as the Concus-Finn condition. As shown in Fig 1, when the Concus-Finn condition is satisfied, the corner angle \( 2\alpha \) must be smaller than \( \pi \); the surface curvature angle \( \delta \) must not be zero, and the surface is concaved. The surface curvature can be solved with trigonometric function [3].

\[
    f = \frac{R}{h} = \frac{\sin \alpha}{\cos \theta - \sin \alpha}
\]  

\( (2) \)
3. The progress of calculation for interior corner flow

In the corner flow, the solution of flow rate and the meniscus shape is very important. The meniscus shape is determined by radius of curvature, meniscus height and the length of meniscus.

In 1990, Geoffrey Mason et al [4] studied the capillary-driven flow in triangular tube with analytical solution, and they found that in the cross section of the tube, the radius of curvature of meniscus in three corner is the same.

In 1996, L. Romero [5] studied the capillary-driven flow in V-shaped groove. He set up a series of nonlinear equations and differential equations of capillary-driven flow using mass conservation equation, and solved them under proper boundary conditions.

In 1996, Mark Weislogel [6] researched the capillary-driven flow in cylindrical containers which has regular polygons in depth. He set up the N-S equations of capillary-driven flow in the corners and follows with an asymptotic analysis employing the lubrication approximation. Then the governing differential equation was solved by a regular perturbation method for the case of the infinite corner.

In 2003, Mark Weislogel [7] studied several kinds of capillary-driven flow in isolated corners like as the cases of capillary rise, a spreading drop, and a constant flow rate condition. He also analyzed the capillary-driven flow in cylindrical containers which has irregular polygons as shown in Fig 2. He investigated the interior corner flow with analytical solutions, and then calculated the radius of curvature $R$, meniscus height $h$, length of meniscus $L$ and the flow rate of capillary flow $Q$.
The corner between two vanes in the surface tension tank is not a sharp one actually, and when the vanes are assembled to the tank, the corner becomes a rounded corner like as Fig 3 generally. In 2006, Yongkang Chen [8] proposed the rounded interior corner model, and solved the governing equations of capillary-driven flow in rounded corner with analytical solution. He also tested the capillary-driven flow in the rounded corner model with drop tower experiments.

There are many constraints in the calculation of interior corner flow, such as Concus-Finn condition and the constraint of meniscus slenderness ratio \( \varepsilon \) et al. The calculation of interior corner flow is mostly focused on one dimensional flow along z-axis up to now, and the more complicated interior corner flow model like spherical and elliptical tank model requires further research.

4. The progress of simulation and experiment of interior corner flow

The numerical simulation and microgravity experiment is absolutely necessary in the research of interior corner flow. The space experiment can provide steady and longtime microgravity condition, but it requires high techs and costs. The drop tower can provide several seconds of microgravity condition with \( 10^{-3} \sim 10^{-5} g \) level. Because of the high costs of microgravity experiment, the numerical simulation is a good way to study interior corner flow. Now the VOF method and Surface Evolver [9] is widely used in microgravity fluid simulation.

Mark Weislogel and Yongkang Chen who are referred in previous section both used Surface Evolver to simulate the corner flow. Then the simulation results are compared with drop tower experiment results.

In 1998, D. Langbein et al [10] proposed the Dynamics of Liquids in Edges and Corners experiment (DYLCO) in the 2nd International Microgravity Laboratory (IML-2) shuttle flight STS-65 to investigate the behavior of capillary surfaces in containers of rhombic cross section which is shown in Fig 4.
In 1996, the VTRE [11] (Vented Tank Resupply Experiment) flight test was carried out by NASA to look at the ability of vane propellant management devices (PMD). The test is a great victory which achieved a great deal of useful data and results. In 2002, Mark Weislogel [3] set up a simplified VTRE model and analyzed it with interior corner flow equations, and compared with VTRE test results. In 2002, Steven H. Collicott [12] set up a full VTRE simulation model with Surface Evolver, the Fig 5 is the simulation of the process when the propellant was vented out from tank.

Fig 4, The model of DYLCO

5. conclusion

There are many achievements and successes in the research of interior corner flow, and also many works should be done if the theories want to find application, such as spherical tank model and various non-sharp interior corner model problems. The interior corner flow is one of the key technologies of on orbit refueling. For keeping up with the sophisticated international space technology, we must speed up the development of on orbit refueling and correlative theoretical research.
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