Numerical investigation of performance of vane-type propellant management device by VOF methods

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Abstract. The orbital propellant management performance of the vane-type tank is so important for the propellant system and it determines the lifetime of the satellite. The propellant in the tank can be extruded by helium gas. To study the two phase distribution in the vane-type surface tension tank and the capability of the vane-type propellant management device (PMD), a large volume vane-type surface tension tank is analysed using 3-D unsteady numerical simulations. VOF methods are used to analyse the location of the interface of the two phase. Performances of the propellant acquisition vanes and propellant refillable reservoir in the tank are investigated. The flow conductivity of the propellant acquisition vanes and the liquid storage capacity of propellant refillable reservoir can be affected by the value of the gravity and the volume of the propellant in the tank. To avoid the large resistance causing by surface tension in an outflow of a small hole, the design of the vanes in a propellant refillable reservoir should have suitable space.

1. Introduction
Propellant management device (PMD) has been used as a kind of surface tension devices in liquid propellant tanks for over forty years. Surface tension forces are negligible in most engineering problems. However, surface tension forces are significant and often dictate the location and the orientation of liquid within tanks in the low gravity environment of orbit vehicles.

A PMD component is defined as a structure which creates as internal, or closed, flow path along which propellant can flow. Using PMD can provide a lightweight, straightforward, easily manufactured, and highly reliable propellant tank for spacecraft. Jaekle analyzed the capability of the PMD by analyzing the influence of vanes[1], sponges[2], galleries[3], traps and troughs[4] to the propellant distribution in the tank with micro gravity. Tam[5,6] proposed a new PMD, which was capable of transferring both gas-free propellant and liquid-free pressurant upon demand. The PMD performance analysis utilized the same design methodology and conservative approaches as all previous PMD design efforts.

The study of propellant distribution in the tank with micro gravity was studied by Chen[8] using experimental test. It is found that increases in gap size, fluid viscosity, contact angle, and vane edge roundness decrease capillary advance rate while increases of the vane thickness and the vane obliquity angle enhance the capillary advance. Estes[9] analyzed the development and implementation of a
process for producing a highly wettable Aluminum PMD for the GPM hydrazine tank. Lenahen[10] investigated the natural frequencies and damping effects of Diaphragm-Implemented spacecraft propellant tanks using computational methods.

In order to study the flow distribution in the propellant tank with micro gravity, two kinds of conditions of a tank with PMD was chosen for the analysis of the performance of the PMD.

2. Propellant Tank Geometry
The study was conducted with a model propellant tank. The structure of propellant tank is shown in Figure 1. The propellant tank has four vanes which are close to the wall of the tank. The PMD consists of four long blades and 8 short blades.

![Figure 1. Propellant tank and PMD](image)

3. Computational Method
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3.1. Volume of fluid model
The volume of fluid (VOF) method determines the shape and location of free surface based on the concept of a fractional volume of fluid.

3.1.1. Continuity Equation. The continuity equation for the mixture is

\[
\frac{\partial}{\partial t} \left( \rho \right) + \frac{\partial}{\partial x_i} \left( \rho u_i \right) = R \tag{1}
\]

\(R\) is the source term. \(\rho\) is the mixture density. \(u_i\) is the mass-averaged velocity.

The properties appearing in the transport equations are determined by the presence of the component phases in each control volume. In a two-phase system, for example, if the phases are represented by the subscripts 1 and 2, and if the volume fraction of the second of these is being tracked, the density in each cell is given by

\[
\rho = \alpha_1 \rho_1 + \alpha_2 \rho_2 = (1 - \alpha_2) \rho_1 + \alpha_2 \rho_2 \tag{2}
\]

\(\alpha\) is the volume fraction of the phase.

The volume fraction equation will not be solved for the primary phase; the primary-phase volume fraction will be computed based on the following constraint:

\[
\alpha_1 + \alpha_2 = 1 \tag{3}
\]
3.1.2. Momentum equation. The momentum equation is

$$\frac{\partial}{\partial t} \rho u_j + \frac{\partial}{\partial x_i} \rho u_i u_j = -\frac{\partial p}{\partial x_j} + \mu \frac{\partial}{\partial x_i} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \rho g_j$$

(4)

$t$ is time. $g$ is the acceleration of gravity. $\mu$ is the coefficient of viscosity.

For the effect of surface tension,

$$\frac{\partial p}{\partial x_j} = -\sigma \frac{\partial}{\partial x_j} \left( \frac{1}{R} \right)$$

(5)

$\sigma$ is the coefficient of surface tension force, $R$ is radius, so the momentum equation can be transformed into,

$$\frac{\partial}{\partial t} \rho u_j + \frac{\partial}{\partial x_i} \rho u_i u_j = \sigma \frac{\partial}{\partial x_j} \left( \frac{1}{R} \right) + \mu \frac{\partial}{\partial x_i} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \rho g_j$$

(7)

3.2. Simulation conditions

The commercial CFD code FLUENT was used to perform the simulations. The SIMPLEC algorithm was used to enforce mass conservation. No slip boundary condition was used to solve the flow on the wall. Two phases in the tank were He and N$_2$H$_4$, and the coefficient of surface tension force was 0.03 N/m. For present unsteady flow calculation, the time step was 0.0001 s. For all calculations, simulations were run until convergence, which was determined by a reduction in the residual error to less than 0.0001.

Three dimensional calculations were performed to investigate the influence of flow distribution in the tank. The model’s grids, which were composed of an unstructured hexahedron and tetrahedron, were developed using ICEM, which is a commercial software package used for CFD discretization. Hexahedral grids were used for each component of the propellant tank. The mesh of the tank is shown in Figure 2.

4. Result and Discussion

4.1. Propellant distributions with small vane in PMD

4.1.1. Propellant for 10% volume. Propellant distributions in the tank with zero gravity are shown in Figure 2. The red color is the propellant, the blue color is gas in the tank. For zero gravity condition, uniform distribution can be seen of the propellant in the tank due to the force of surface tension. The propellant in the tank flow along the vanes and the height of the propellant along the right vane reaches half of the height of the tank for 6.0s. Due to the scale of the PMD is small and the height of the vanes in the PMD is in accordance with the cylinder in the PMD, the surface tension force becomes a resistance at the top of the vane in the PMD. The propellant will not fill the PMD. Figure 3 shows propellant distributions in the tank with 0.001 gravity at -X coordinate. The flow in the PMD also has the same result as shown in Figure 2, but the propellant tends to flow to the X coordinate.

4.1.2. Propellant for 5% volume. Propellant distributions in the tank with zero gravity are shown in Figure 4. Propellant distributions in the tank with 0.001g gravity are shown in Figure 5. When the residual propellant is 5% volume of the tank, small gravity will not affect the distribution of the propellant in the tank. The propellant firstly flows into the PMD and then a little back to the tank. So it can be seen the addition of the volume of propellant in the PMD at first and the volume gradually decreases when $t>2.0$ s.
It can be concluded that the store of propellant by the vane is stronger than the PMD with lower height vanes. The surface tension force becomes resistance force at the top of the vanes in the PMD. The PMD will not be filled up by the propellant.

Figure 6 shows the flow rate between the tank and the PMD with 10% volume of propellant in the tank and the volume of propellant in the PMD is shown in Figure 7. The flow rate has a linear relationship with time when t<1.8s, and the flow rate has a maximum value at t=1.8s. The flow rate gradually decreases when t>1.8s and the slope of the flow rate line reduces. When t=7.0s, the flow rate decrease to 2.0ml/s. The propellant will not maintain the thrust and the PMD needs to be improved.

Figure 2. Zero gravity condition

Figure 3. 0.001 gravity in –X coordinate
4.2. Optimization of propellant management device

To improve the resistance force at the top of the vanes, the short vanes in the PMD are lengthened and the structure of the PMD are shown in Figure 8. The distance between the top of the vane and the upper casing of PMD is $l$.

The result of the propellant distribution in the tank for the improved PMD is shown in Figure 9. The result is calculated with 0.001 gravity in $-X$ coordinate. The propellant will reach the top of the
PMD when \( t = 1.5 \text{s} \). Because the distance between the top of vane in the PMD and the up casing is small, the propellant will flow to the up hole of the PMD, and the hole for exhausting gas in the PMD is plugged up. Lot of gas will be left in the PMD. It will affect the stable working of the thrust. Figure 10 shows the flow rate between the tank and the PMD. The lengthen of the vane in the PMD increases the flow rate.

![Figure 8. Structure of the improved PMD](image)

![Figure 9. Propellant distribution for the improved PMD](image)

![Figure 10. Flow rate between the tank and the PMD](image)

In order to let the gas in the PMD flow into the tank through the up hole, the distance between the top of vane in the PMD and the up casing is increased and the improved PMD-2 is shown in Figure 11. The result of the propellant distribution for the improved PMD-2 is shown in Figure 12. The addition of the distance will improve the propellant distribution in the PMD and the hole in the PMD will not be plugged up. The flow rate between the tank and the PMD-2 is almost 9 ml/s. The performance of the improved PMD-2 can maintain the working of the thrust.
5. Conclusion
This paper involves the propellant distribution and optimization of a PMD in a tank. The VOF model could be used to simulate the flow in a PMD with micro gravity. Flow distribution can be influenced by the change of the value of gravity when the gravity is larger than 0.001g. For the scale of the PMD is small, the surface tension force may become a resistance at the top of the vane in the PMD. The avoidance of the resistance is to modify the shape of PMD and choose a suitable distance for the PMD structure. The PMD is one of the key components in the tank, it determines the flow rate between the PMD and the tank.
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References
[1] Jaekle D E 1991 Propellant management device conceptual design and analysis: Vanes AIAA/SAE/ASME/ASEE 27 Joint Propulsion Conf. (Sacramento, CA, 24-26 June 1991)
[2] Jaekle D E 1993 Propellant management device conceptual design and analysis: Sponges AIAA/SAE/ASME/ASEE 29 Joint Propulsion Conf. (Monterey, CA, 28-30 June 1993)
[3] Jaekle D E 1997 Propellant management device conceptual design and analysis: Galleries AIAA/SAE/ASME/ASEE 33 Joint Propulsion Conf. (Monterey, CA, June 28-30, 1997)
[4] Jaekle D E 1995 Propellant management device conceptual design and analysis: Traps and troughs AIAA/SAE/ASME/ASEE 31 Joint Propulsion Conf. (San Diego, CA, 10-12 June 1995)
[5] Tam W D and Jaekle J 2005 Design and Manufacture of an Oxidizer Tank with Surface Tension PMD AIAA 2005 3734
[6] Tam W H, Ballinger I, Jaekle Jr D E 2006 Conceptual Design of Space Efficient Tanks 42nd AIAA Joint Propulsion Conf. & Exhibit (Sacramento, CA, 9-12 July 2006)
[7] Tam W and Ballinger I 2008 Surface Tension PMD Tank for On Orbit Fluid Transfer 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conf. & Exhibit (Hartford, CT, 21-23 July 2008)
[8] Chen Y K and Collicott S H 2004 Experimental Study on the Capillary Flow in the Vane-Wall Gap Geometry 42nd AIAA Aerospace Sciences Meeting and Exhibit (Reno, Nevada, 5-8 Jan 2004)
[9] Estes R H 2012 Development and Implementation of a Process for Producing a Highly Wettable Aluminum PMD for the GPM Hydrazine Tank 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit (Atlanta, Georgia, 30 July-01 Aug 2012)
[10] Lenahen B, Bernier A and Gangadharan S 2012 A Computational Investigation for Determining the Natural Frequencies and Damping Effects of Diaphragm Implemented Spacecraft Propellant Tanks 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit (Atlanta, Georgia, 30 July-01 Aug 2012)