Numerical simulation of the flow distribution in a trap of a propellant tank with micro gravity

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Abstract. A trap device is defined as a closed structure which holds and provides a specific quantity of propellant using the surface tension forces. A trap in a vane-type PMD is investigated. The influence of the cone angle of the trap and flow distributions with different conditions in space are investigated. The VOF model could be used to simulate the flow distribution in a trap with zero or small gravity condition. The optimal angle for the trap is \( \alpha = 45^\circ \) and it has the best result of expulsion efficiency of the propellant tank. The trap can be full filled with propellant after 21 second at zero gravity condition and 37 second at north-south insurance condition. A gas bubble left in the trap at the end of the refilling process. There is no flow distribution change in the trap when the trap is full filled at reverse gravity condition and sink condition.

1. Introduction
Surface tension forces are negligible in most engineering problems. However, in the low gravity environment of orbiting vehicles, surface tension forces are significant and often dictate the location and orientation of liquid within vessels, conduits, etc. By carefully designing structures within a propellant tank, one can utilize these forces to ensure gas free propellant delivery. These structures have come to be known as propellant management devices or PMDs.

Traditionally PMDs are designed for each specific mission scenario and tank size. As a result PMDs can be found in numerous sizes and configurations. PMDs can be classified into three broad categories: partial control devices, total control devices, and total communication devices. By definition, communication PMDs provide gas free propellant delivery by establishing a communication path between the bulk of the propellant and the outlet or another device component such as a sponge. The vane type PMD is such a device.

Sharipov[1] investigated gaseous mixture flow of a PMD through a long tube at arbitrary Knudsen numbers. Jaekle analyzed the capability of the vane-type PMD by analyzing the influence of vanes, sponges, galleries, traps and troughs[2-4] to the propellant distribution in the tank. Tam[5] 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. Hu[6] studied the influence of width and angle on the performance of a vane-type PMD. It was found that increase of width of the vane would improve the flow rate along the vanes, but it also decreases the climbing height of the propellant. Liu[7] analyzed
the management performance with different operating condition of a vane-type tank by numerical simulation. Zhuang[8] investigated the natural frequencies and damping effects of Diaphragm-Implemented spacecraft propellant tanks using computational methods.

A kind of trap in a vane-type PMD is investigated. The influence of the cone angle of the trap was studied. Flow distributions with different conditions in space were investigated.

2. Trap Geometry
Trap offers a reservoir of propellant usable during high acceleration maneuvers. A trap retains liquid even when horizontal or inverted by using the surface tension forces present in a wetted porous element. Propellant will remain within the trap against the hydrostatic forces only if the bubble point of the porous element is not exceeded. If the maximum pressure difference across the porous element established by surface tension (the bubble point) is insufficient to balance the hydrostatics and flow losses, gas will enter the trap through the porous element and the trap will leak. By choosing a smaller pored porous element, higher accelerations and/or larger distances can be accommodated. The structure of trap in a vane-type PMD is shown in figure 1 and figure 2. The trap has 24 small vanes. Three kinds of angles $\alpha$ (45°, 48° and 51°) of the trap are studied.

![Figure 1. Trap of the PMD.](image1)

![Figure 2. Vanes structure of trap](image2)

Table 1. Parameters of the model pump-turbine

| Parameter                              | Value |
|----------------------------------------|-------|
| rated head (m)                        | 52.4  |
| rated discharge (m$^3$/s)             | 0.45  |
| rotational speed (rpm)                | 1200  |
| runner inlet diameter (m)             | 0.3   |
| numbers of blades                     | 9     |
| numbers of vanes                      | 20    |

3. Computational Method

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.

1) Continuity Equation
The continuity equation for the mixture is

$$\frac{\partial}{\partial t} (\rho) + \frac{\partial}{\partial x_i} (\rho u_i) = R$$

where $R$ 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
\[
\rho = \alpha_1 \rho_1 + \alpha_2 \rho_2 = (1-\alpha_2) \rho_1 + \alpha_2 \rho_2
\]  
(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:

\[
\alpha_1 + \alpha_2 = 1
\]  
(3)

2) Momentum equation

The momentum equation are,

\[
\frac{\partial}{\partial t} \rho u_j + \frac{\partial}{\partial x_i} \rho u_i u_j = -\frac{\partial p}{\partial x_i} + \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \rho g_j
\]  
(4)

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

For the effect of surface tension,

\[
\frac{\partial}{\partial x_j} \sigma \left( \frac{1}{R} \right)
\]  
(6)

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

\[
\frac{\partial}{\partial t} \rho u_j + \frac{\partial}{\partial x_i} \rho u_i u_j = \sigma \left( \frac{1}{R} \right) + \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \rho g_j
\]  
(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 using to solve the flow on the wall. Two phases in the tank were He and N\(_2\)H\(_4\). Properties of He and N\(_2\)H\(_4\) are shown in Table 2. 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.

| Fluid  | Temperature(℃) | Density(g/cm\(^3\)) | Viscosity (10\(^{-4}\)Pa.s) | Surface tension coefficient (dyn/cm) |
|--------|----------------|---------------------|-----------------------------|-------------------------------------|
| N\(_2\)H\(_4\) | 20 | 1.008 | 9.51 | 74.76 |
| He     | 20 | 0.1625 | 0.199 | / |

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.

4. Result and Discussion

4.1. Optimization of cone angle

The reverse gravity condition in space of the satellite is the worst condition for the trap to manage the propellant at the end of life. Results of propellant distribution with different cone angle at the reverse gravity condition and the end of life are shown in figure 3-5 (black color denotes the propellant). The trap is used to provide continuous propellant to the thruster. The flow rate of the outlet of the trap is very important. It can be seen that the flow rate will decrease with the increase of cone angle. At the end of life, the flow rate from the trap to the thruster gradually decreases to zero and lot of propellant left in the trap which can not be discharged. The propellant lost in the trap also determines the expulsion efficiency
of the tank. Few propellants left in the trap are the purpose to design a PMD. The mass of the propellant left in the trap with different cone angles is summarized in Table 3. The minimum mass of the three model is α=45°. Therefore, it can make a conclusion that the optimal angle for the trap is α=45°.

![Figure 3. Propellant distribution and flow rate curve at α=45° in reverse gravity condition.](image3)

![Figure 4. Propellant distribution and flow rate curve at α=48° in reverse gravity condition.](image4)

![Figure 5. Propellant distribution and flow rate curve at α=51° in reverse gravity condition.](image5)

| α/°  | Mass/kg |
|------|---------|
| 45   | 9.7215  |
| 48   | 9.9340  |
| 51   | 9.8951  |

**Table 3.** Mass of the propellant left in the trap

4.2. **Trap performance analysis**

Refillable traps use the hydrostatics and dynamics created by the main engine settling acceleration to eject the gas ingested during ignition; refilling the trap. The filling time for a trap is very important for the propellant system.

4.2.1. **Refilling process of the trap.** The refilling process of the trap with zero gravity condition is shown in figure 6 (black color denotes the propellant). Propellant climbs quickly at the center of the trap caused
by the minimum clearance in the middle part. Due to the contact angle of the propellant is small, the propellant climbs along the cone wall to the top sharp region. Then the propellant gradually fills the sharp region and the gas in the trap is expelled from the gas outlet of the trap. The trap is full filled with propellant after 21 second and a gas bubble left in the trap at the end.

Figure 6. Refilling process of the trap with zero gravity condition

4.2.2. Reorientation at reverse gravity condition and sink condition. Reorientation of the propellant in the trap at reverse gravity condition is shown in figure 7 (black color denotes the propellant). The gravity is $5 \times 10^{-4} g_0$. It can be seen that the trap can hold the propellant stay in the tray and no flow distribution change happened.

Figure 7. Reorientation of the propellant in the trap at reverse gravity condition

Reorientation of the propellant in the trap at sink condition is shown in figure 8 (black color denotes the propellant). The gravity is $5 \times 10^{-4} g_0$. There also has no flow distribution change in the trap.
4.2.3. North-south insurance condition. At north-south insurance condition, the gravity direction is the same with X direction. The refilling process of the trap with north-south insurance condition is shown in figure 9 (black color denotes the propellant). The gravity is $5 \times 10^{-3} g_0$. Propellant behaviors in the trap are the same with refilling process of the trap with zero gravity condition. The trap is full filled with propellant after 37 second and also a gas bubble left in the trap at the end. It can be seen that the north-south insurance condition will not influence the refilling process of the propellant for this trap.

5. Conclusion
A trap device is defined as a closed structure which holds and provides a specific quantity of propellant using the surface tension forces. This paper involves the propellant distribution and optimization of a vane type trap of a PMD in a tank. The VOF model could be used to simulate the flow distribution in a trap with zero or small gravity condition. The optimal angle for the trap is $\alpha = 45^\circ$ and it has the best result of expulsion efficiency of the propellant tank. The trap can be full filled with propellant after 21 second at zero gravity condition and 37 second at north-south insurance condition. A gas bubble left in the trap at the end of the refilling process. There also has no flow distribution change in the trap when the trap is full filled at reverse gravity condition and sink condition.

Acknowledgment
This research was financially supported by the National Natural Science Foundation of China 51406010.
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