Numerical simulation of the flow in a vertical vane type tank with micro downward acceleration

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Abstract. Vane type propellant tank is widely used in propellant system of satellite at present for that it can be refuelled in space. The performance of a vertical vane type tank is determined by propellant management device (PMD). The VOF model with commercial code (Fluent) was used to simulate the gas-liquid distribution with micro downward acceleration. Two kinds of volume fractions of liquid were chosen for the simulation. The flow rate of the liquid can reach 1300 ml/s. The potential energy caused by gravity for the initial conditions would be released in three seconds. The liquid in the tank would keep steady state in 28 seconds. These results could provide a reference for high acceleration maneuvers of a satellite.

1. Introduction

Surface tension forces are obvious in space with micro acceleration and it can determine the liquid distribution in a tank. Traditional net type tank used in space is hardly to be refilled by liquid in PMD when there has gas inside PMD. Tank with vertical vane is a new type tank for the propellant which can be refuelled in space. In order to ensure gas free propellant delivery for a thruster, the location of gas and liquid in a vertical vane type tank must be evaluated after the tank geometry is designed.

Two methods were used to evaluate the control performance of vertical vane in micro gravity. One way was numerical simulation. Hu[1] studied the influence of parallel vane in a tank. The performance of the parallel vane was studied with different widths and angles. It was found that the flow rate increases with larger width of the vane, while the climbing height will decrease. Liu[2] numerical studied the flow distribution in a tank with parallel vane in different accelerations. Zhuang[3] studied the damping effects and the basic frequency of the propellant in a tank by numerical simulation. The other way is experiment. Rui[4] investigated the location of gas and liquid flow in a sphere vane type tank using different fractions of propellant as well as different acceleration vectors. Bolledu[5] experimental studied the capillary flow in a vane type tank by drop towers. Li[6] investigated the capillary flow in a vane-type propellant tank. Zhuang[7] performed an drop tower test to study the flow distribution and refillable performance in a reservoir with micro gravity condition.

A new kind of tank with vertical vanes is established. Flow distributions with micro downward acceleration in space were investigated.
2. Tank Geometry
The model of the tank with vertical vanes is shown in Fig. 1. The tank is formed by two hemisphere parts and a cylinder part. The PMD has 12 small vanes, 4 large blades and 4 vanes. The diameter of the tank is 476 mm, and the height of the cylinder part is 396 mm.

| Parameter                        | Value |
|----------------------------------|-------|
| Diameter of the tank (mm)        | 476   |
| Height in cylinder part (mm)     | 396   |
| Number of blade                  | 4     |
| Numbers of vanes                 | 4     |
| Numbers of small vanes           | 12    |

3. Computational Method

3.1 Volume of fluid model
The volume of fluid (VOF) method is usually used to simulate the gas and liquid separative flow and capture the gas-liquid interface based on a fractional volume of fluid.

The continuity equation for the gas and liquid flow is

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

\( R \) is the source term, \( \rho \) is the mixture (gas and liquid) density, \( u_i \) is the averaged velocity for mass.

For gas and liquid flow, for example, the density with different location is given by

\[ \rho = \alpha_1 \rho_1 + \alpha_2 \rho_2 = (1 - \alpha_2) \rho_1 + \alpha_2 \rho_2 \]  

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

The volume fraction equation is shown as follows,

\[ \alpha_1 + \alpha_2 = 1 \]  

3.2 Simulation conditions
FLUENT was used to simulate the gas and liquid distribution in the tank with VOF model. The mass conservation is performed by SIMPLEC algorithm. No slip boundary condition on the wall was used.
during the simulation. The gas in the tank is He and the liquid is N₂H₄. Properties in temperature 20 ℃ of He and N₂H₄ are shown in table 1. The surface tension coefficient between the gas and liquid is 74.76 dyn/cm. The time step for the unsteady flow was 0.0001 s. For all calculations, simulations should be convergence with residual error less than 0.0001.

| Fluid  | Temperature(℃) | Density(g/cm³) | Viscosity (10⁻⁴ Pa.s) | Surface tension coefficient (dyn/cm) |
|--------|----------------|----------------|-----------------------|------------------------------------|
| N₂H₄  | 20             | 1.008          | 9.51                  | 74.76                              |
| He     | 20             | 0.1625         | 0.199                 | /                                  |

Numerical simulations were performed to study the location of gas and liquid with different downward accelerations in the tank. The model’s grids are divided into four part using unstructured hexahedron and tetrahedron.

4. Result and Discussion
The distribution of gas-liquid interface in the relocation process with 25% volume fraction is shown in Fig. 3. The propellant climbed to the top of the tank along the central column at six seconds. At 28 seconds, the force for the fluid in the tank is in equilibrium, and the distribution of gas-liquid interface is stable. When the propellant in the tank is within 12 seconds, the propellant on the guide plates on both sides merges with the propellant on the central column, which constrains the gas in the internal area of the tank. The distribution of gas-liquid interface in the relocation process with 50% volume fraction is shown in Fig. 4. It has the same rule with volume fraction is 25%. The distribution of gas-liquid interface is stable at 28 seconds.

The flow rate changes with time is shown in Fig. 5. The potential energy caused by gravity will be totally released when the flow rate of liquid reached the maximum value. It can be found that the time for the complete release of potential energy is shorter than three seconds. The maximum flow rate of liquid along the four vanes is about 1300 ml/s.

5. Conclusion
Two kinds of volume fractions of liquid in the vane type tank were evaluated. The flow rate of the liquid can reach 1300 ml/s. The potential energy caused by gravity for the initial conditions would be released in three seconds. The propellant climbed to the top of the tank along the central column at six seconds. The liquid in the tank would keep steady state in 28 seconds. These results could provide a reference for high acceleration maneuvers of a satellite.
Figure 4. Relocation process of liquid in tank with volume fraction is 50%.

Figure 5. Liquid flow rate during relocation process with different volume fractions.

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