Numerical analysis and experiment research on fluid orbital performance of vane type propellant management device

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Abstract. Vane type propellant management device (PMD) is one of the key components of the vane-type surface tension tank (STT), and its fluid orbital performance directly determines the STT’s success or failure. In present paper, numerical analysis and microgravity experiment study on fluid orbital performance of a vane type PMD were carried out. By using two-phase flow model of volume of fluid (VOF), fluid flow characteristics in the tank with the vane type PMD were numerically calculated, and the rules of fluid transfer and distribution were gotten. A abbreviate model test system of the vane type PMD is established and microgravity drop tower tests were performed, then fluid management and transmission rules of the vane type PMD were obtained under microgravity environment. The analysis and tests results show that the vane type PMD has good and initiative fluid orbital management ability and meets the demands of fluid orbital extrusion in the vane type STT. The results offer valuable guidance for the design and optimization of the new generation of vane type PMD, and also provide a new approach for fluid management and control in space environment.

1. Introduction
Vane type PMD which is the core part of the vane-type STT mainly comprises of vane type structure parts, such as propellant acquisition vanes (PAV) and propellant refillable reservoir (PRR) [1-2]. Basing on surface tension, the PMD is a new device which implements initiative and complete fluid management and control in space environment, and its operational principle is that by vane type parts it can achieve the separation between liquid and gas, fluid transmission, storage, orientation and discharge, which overcomes the shortcomings of net type PMD, such as complicated structure, being polluted easily, heavy weight, poor performance of volume expanding and incapable filling and discharge fluid repetitively. The PMD is currently the most advanced fluid management and control in space environment, and it can satisfy kinds of flux requirements and be applicable to different microgravity environment, especially large satellite platform with relatively more small microgravity level. So far, main geostationary orbit satellites internationally have applied the vane-type STTs, such as A2100, SB4000, and ETS-Ⅷ [3-5].

Fluid orbital management performance of PMD will directly determine the orbital STT’s success or failure. However, because of restrictions on structure function of vane-type PMD, it is unable to carry out long-term verification test on fluid management performance of the PMD, so numerical analysis on fluid orbital management performance of the PMD becomes especially important and is required to complete first, which can offer valuable guidance for the design and optimization of the PMD. Then verification test and research on fluid orbital management performance of PMD and results of numerical analysis must be carried out by microgravity drop tower tests. Researchers from abroad
have studied mechanism of fluid orbital performance of vane type PMD in the microgravity from the early 70’s, and achieve a great deal of findings through tremendous manpower and resources. While others in our country began researching that in the twenty-first century, and gain some valuable achievements [6-11]. In present paper, aiming at a vane type PMD, rules of its fluid management, transmission and distribution are revealed by numerical analysis and microgravity drop tower tests, which provide valuable guidance and datum support for design and optimization of vane-type STT.

2. Numerical model and test system of vane type PMD

In the paper, the vane type PMD shown in figure 1 mainly comprises of a PRR and four PAV, which can implement initiative and complete propellant orbital management and control. Four PAV arranged in four directions +X, -X, -Y, and +Y are used for transferring propellant. The PRR wrapped up by the inside and outside cones is located at liquid outlet of STT’s bottom, and a small PRR is arrange in the PRR, which is a radial wedge structure comprised of some blades. The PRR acts on storing and supplying propellant for STT.

2.1. Numerical model

By using two-phase flow model of volume of fluid (VOF), rules of fluid distribution in vane-type STT under microgravity environment are gotten by numerically calculating.

VOF model is an algorithm which is to solve two-phase flow with gas and liquid and calculate flow of fluid free surface. By leading in fluid volume fraction function and its control equation, the algorithm can show the density of mixed fluid and make tracks for positions of fluid free surface. Due to laminar flow generally in vane-type STT, basic equations of VOF model comprise of the physical equation, the continuity equation and the momentum equation.

The physical property of fluid is determined by volume fraction of different phases in mixed fluid, and the physical equation expresses physical property of different volume fraction. Owing to only two-phase mixed flow in the STT, density properties equation of mixed fluid is given below.

$$\rho = \alpha_1 \rho_1 + \alpha_2 \rho_2, \quad \alpha_1 + \alpha_2 = 1$$

Where $\rho$ is the density of mixed fluid, where $\alpha_1$ and $\alpha_2$ are volume fractions of the first phase and the second phase respectively, and where $\rho_1$ and $\rho_2$ are densities of the first phase and the second phase respectively, which are given values.

Basic expression of the fluid continuity equation is given below.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho u) = R$$

Where $u$ is velocity of mixed fluid, and where $R$ is the source term.

According to equation (1) and equation (2), the transport equation of different phase volume fraction is gotten and given below.
\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} \left( \alpha_{q} u \right) = R \tag{3}
\]

Where \( \alpha_{q} \) is volume fraction of the \( q \)-th phase, and where \( R \) is caused by net phase transition. Because the value of \( R \) is very small in this model, it is negligible while solving the equation (3).

The momentum equation of mixed fluid is given below.
\[
\frac{\partial}{\partial t} (\rho u_{j}) + \frac{\partial}{\partial x_{i}} (\rho u_{j} u_{i}) = - \frac{\partial p}{\partial x_{j}} + \mu \left( \frac{\partial u_{j}}{\partial x_{j}} + \frac{\partial u_{j}}{\partial x_{i}} \right) + \rho g_{j}, \tag{4}
\]

Where \( p \) is inner pressure of the STT, where \( u_{j} \) and \( u_{i} \) are liquid phase velocity and gas phase velocity respectively, where \( x_{j} \) and \( x_{i} \) are liquid phase position and gas phase position respectively, where \( t \) is the time, where \( g_{j} \) is microgravity acceleration, and where \( \mu \) is coefficient of viscosity.

Due to the action of surface tension, the equation in the gas-liquid interface is given below.
\[
\frac{\partial p}{\partial x_{j}} = -\sigma \left( \frac{1}{r} \right) \tag{5}
\]

Where \( \sigma \) is coefficient of surface tension, and where \( r \) is surface curvature radius. According to equation (4) and equation (5), the final momentum equation of mixed fluid is given below.
\[
\frac{\partial}{\partial t} (\rho u_{j}) + \frac{\partial}{\partial x_{i}} (\rho u_{j} u_{i}) = \sigma \left( \frac{1}{r} \right) + \mu \left( \frac{\partial u_{j}}{\partial x_{j}} + \frac{\partial u_{j}}{\partial x_{i}} \right) + \rho g_{j}, \tag{6}
\]

According to the structure of the PMD shown in figure 1, calculation model of performance analysis is established. The computing grids are generated by using the form of structured grids, and the grids near walls of structure are further thinner and denser. The grid number of the model is approximately one million, and figure 2 shows the numerical model of grids.

While solving the model, all the walls are set to boundary condition of solid walls, whose boundary condition is without penetration and slither. The flow near walls of structure is simulated by using logarithmic function.

The computational domain includes liquid and gas, and the distributions of liquid and gas in the domain are confirmed via setting volume fraction of each phase in advance. Now, the first phase is nitrogen, and the second phase is the propellant named ADN.

2.2. Test system and abbreviate model

Microgravity drop tower tests which are most usual in the means of microgravity tests can provide short microgravity time, but can supply relatively low microgravity level. In the paper, these microgravity tests have been carried out by the hundred meters drop tower of National Microgravity Laboratory (NML) [12]. The free fall experiment facility of the drop tower provides microgravity time which is about 3.5s, and the facility comprises of the falling module, the deceleration and recovery system, the release system, the control system, the measurement system, and auxiliary equipments and so on. The falling module is the core part of the facility, and is the important and special equipment used for loading test models in the drop tower test system. The module is divided into two groups: the internal double module and the internal single module. The microgravity level provided by the internal double module grades between \( 10^{-4} g_{0} \) and \( 10^{-5} g_{0} \), and The microgravity level provided by the internal single module grades between \( 10^{-2} g_{0} \) and \( 10^{-3} g_{0} \).

According to the requirement of microgravity drop tower experiment research, the internal single module is used for the tests in the paper, and the test system with abbreviate models is built, which is shown in figure 3 and figure 4 below. The test system consists of abbreviate models, the test bracket, the lighting device and the picture acquisition device and so on, and can be used for microgravity test
and verify flow behaviors of vane type PMD. In the system, the high resolution camera with CCD is using for recording fluid climbing process, distribution and reorientation process in abbreviate models.

Figure 5 below shows the abbreviate model of the vane-type STT used in the microgravity tests, which consists of a vane type PMD and shells. The PMD uses titanium alloy material, and these shells use plexiglass material whose light transmittance is approximately 90%, so it is easy to observe test results. Anhydrous ethanol is used for the test medium of propellant, its static contacting angles with titanium alloy and plexiglass are approximately 0°.

Figure 3. Sketch map of test system.  
Figure 4. Sketch map of assembly placement.

Figure 5. Sketch map of abbreviate model structure.

3. Results and discussions

3.1. Results and discussions of numerical analysis

When the microgravity acceleration under fluid-sinking mode is $5 \times 10^{-5} \text{g}_0$, the reorientation process with filling ratio 10% is shown in figure 6 below, and in the figure the darker park is fluid and the lighter part is gas. Seeing from figure 6, owing to the driving of surface tension, the fluid is transferred to the PRR by the PAV and the filling phase of PRR is beginning. The fast filling fluid into PRR has been achieved under the small PRR and the fluid can’t block the through vent on the inside cone of PRR, it makes sure that the gas in PRR discharges smoothly during the filling phase, and there are none phenomena or trend of fluid cutoff on PAV during the filling phase. After 13s of the reorientation process, the PRR has been nearly filled with fluid. The results of numerical analysis coincide with the desired effects of design.
Then the discharging process under microgravity lateral acceleration with $1\times 10^{-3}g_0$ is shown in figure 7 below, and in the figure the darker park is fluid and the lighter part is gas. The fluid surface distribution of the 8th second during the above-mentioned reorientation process is selected as the initial condition of the discharging process, and the discharging rate of flow is 8ml/s. According to figure 7, during the discharging process, not only the fluid in PRR is discharged providing some flux, but also the fluid outside PRR is discharged for providing the other flux via wickets under PRR. There are none fluid cutoff on PAV or in PRR during the discharging process, so the vane type PMD can satisfy the flow requirement of 8ml/s. The results of numerical analysis achieve the desired effects of design.

When the microgravity lateral acceleration is $1\times 10^{-3}g_0$, the reorientation process with filling ratio 2% is shown in figure 8 below, and in the figure the darker park is fluid and the lighter part is gas. If the driving of fluid surface tension isn’t enough during the end phase of STT’s life, then it is possible to appear some bad phenomenons, such as inadequate flow and liquid discharging with some gas. But seeing from figure 8, owing to the driving of surface tension, fluid mainly stores near PRR and the fast filling fluid into PRR has been achieved still under the small PRR, and fluid covers the liquid outlet of STT’s bottom throughout. So it makes sure that some fluid without gas can be discharged out from STT, and it infers that the orbital extrusion efficiency of STT is more than 98%, which satisfies assignment requirement of fluid orbital extrusion. The results of numerical analysis also achieve the desired effects of design.

3.2. Results and discussions of microgravity drop tower tests
Figure 9 below shows the fluid reorientation process with filling ratio 10% in the abbreviate model under fluid-sinking mode. Before releasing the falling module, fluid surface mainly maintain level surface, and all the microgravity time is 3.5s. As shown in figure 9, by using the driving of surface tension, the fluid rapid climbs along the gap region between PAV and inner walls of STT after
releasing the falling module, which is due to the smaller curvature radius of the gap region. When the microgravity time is 1.5s, the fluid has climbed along PAV nearly to STT’s top, and a concave liquid surface between PRR and inner walls is shaped slowly during the climbing process. After 1.5s, liquid surface and radius along PAV are mainly invariant, but the concave meniscus dents quickly, because the fluid between PRR and inner walls is fast absorbed into PRR, so it indicates that the PRR has good fluid storage ability. Meanwhile fluid covers the liquid outlet of STT’s bottom throughout. The experiment results indicate that the vane type PMD has good and initiating fluid orbital management ability and can availably achieve the separation between fluid and gas interface and providing propellant without gas for thrusters.

Figure 9. Reorientation process with filling ratio 10% in the abbreviate model.

Figure 10 below shows the fluid reorientation process with filling ratio 2% in the abbreviate model under fluid-sinking mode. According to figure 9, by using the driving of surface tension, the fluid rapid climbs along the gap region between PAV and inner walls of STT and a concave liquid surface between PRR and inner walls is shaped under microgravity environment. After 1.0 s, the fluid between PRR and inner walls is fast absorbed into PRR, which indicates that the PRR has good fluid storage ability. Finally the fluid mainly reserves in PRR and the region between PRR and inner walls and covers the liquid outlet of STT’s bottom whole, so it makes sure that some fluid without gas can be discharged out from the abbreviate model, and it infers that the orbital extrusion efficiency of the abbreviate model is more than 98%. The experiment results indicate that the goal of microgravity experiment verification in principle on fluid distribution condition at the end of STT’s life and extrusion performance of STT has been achieved.

Figure 10. Reorientation process with filling ratio 2% in the abbreviate model.

Comparing the results mentioned above, the researchers find the results of numerical analysis and the results of microgravity experiment study are relatively identical and attain the effect of verifying analysis and tests each other, and the numerical analysis are correct and effective.

4. Conclusions
Numerical analysis and microgravity experiment study on fluid orbital management performance of a vane type PMD have been carried out, and fluid management characteristic and fluid transmission and distribution rules of the vane type PMD have been obtained under microgravity environment. The results of numerical analysis and microgravity experiment study are relatively identical, and the results offer valuable guidance for the design and optimization of new generation vane type PMD and have been used for the development of vane-type STT, which promote the update of domestic STT products.
The analysis and tests results show that the vane type PMD has good and initiative fluid orbital management ability and meets the demands of fluid orbital extrusion in the vane type STT. Meanwhile the vane type PMD provides a new approach for fluid management and control and is favor to enhance the technical level of fluid management and control in space environment.

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