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Numerical simulation and microgravity experiment of fluid flow in the vane type tank

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Abstract. Propellant tank is an important component of spacecraft, which determines the life of spacecraft. As a key unit for storage and management fluid on the spacecraft, the vane type tank can provide liquid without gas for thrusters. And the propellant management device(PMD) is the core component in the tank. In the paper, numerical simulation and microgravity experiment have been carried out to study the performance of propellant management. By using a VOF two-phase flow model, the fluid behaviour in tank is numerically simulated. By microgravity drop tower tests, the fluid distribution is obtained actually. The results from numerical simulation are in good agreement with ones from the microgravity drop tower tests. It shows that the PMD of the vane type tank can availably achieve the separation between liquid and gas interface and providing liquid without gas in microgravity environment.

1. Introduction

Propellant tank is an important component of spacecraft, which determines the life of spacecraft. At present, the main propellant tank of spacecraft is surface tension tank. As a key unit for storage and management fluid on the spacecraft, the vane type tank can provide liquid without gas for thrusters. And the core part of the vane type tank is the propellant management device(PMD). The principal advantages of the vanes type tank are light, reliable, repeatable, slosh suppression. The vane type tank with big vanes is one of the most advanced new type propellant tanks, which can guide and sponge fluid[1~5]. The working environment of the vane type tank is the microgravity environment, in which the gravity is not the dominant factor. Therefore the study of the fluid behavior in microgravity environment is crucial. The microgravity drop tower test can be used to study the fluid behavior of the vane type tank, but the experiment verification of the vane type in microgravity environment couldn't be given for a long time. Therefore numerical simulation is necessary for the study of the vane type tank. In this paper, by using a VOF two-phase flow model, the fluid behavior in microgravity environment in tank is numerically simulated to research the performance of the van type tank. Microgravity drop tower tests are carried out. Through comparative the results of numerical simulation and experiment, the fluid distributing rule is obtained[4~6].

2. Numerical simulation

2.1. Volume of fluid method

In this paper, by using a VOF two-phase flow model, the fluid flow characteristics in the tank are numerically simulated[7~10]. The volume of fluid (VOF) method is a free-surface modeling technique for tracking and locating the free surface. It belongs to the class of Eulerian methods which are characterized by a mesh that is either stationary or is moving in a certain prescribed manner to accommodate the evolving shape of the interface. VOF is an advection scheme—a numerical recipe that allows the programmer to track the shape and position of the interface. It is a scalar function, defined as the integral of a fluid's characteristic function in the control volume, namely the volume of a computational grid cell. Due to laminar flow generally in vane type tank, the basic equation of VOF model comprise of physical equation, continuity equation and momentum equation.

2.1.1. Physical equation. The physical property of fluid is determined by volume fraction of different phases in mixed fluid, and the physical equation express physical property of different volume fraction. There is only two-phase mixed flow in the tank, so density properties equation of mixed fluid is given below.

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

$\rho$is the density of mixed fluid, $\alpha_1$and α_2 are the volume fractions of the two phase, ρ_1 and ρ_2 are the densities of the two phase, which are given values.

2.1.2. Continuity equation. The continuity equation for the mixture is

$$\frac{\partial}{\partial t}(\rho) + \frac{\partial}{\partial x_i}(\rho u_i) = R \tag{2}$$

$u_i$is velocity of mixed fluid, R is the source term.

2.1.3. Momentum equation. The momentum equation of mixed fluid is

$$\frac{\partial}{\partial t}\rho u_j + \frac{\partial}{\partial x_j}\rho u_i u_j = -\frac{\partial p}{\partial x_j} + \mu\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \rho g_j \tag{3}$$

p is the pressure of the tank, u_j and $u_i$are velocity of liquid phase and gas phase respectively, x_j and x_i are liquid phase position and gas phase position respectively, t is the time, g_j is microgravity acceleration, and μ is coefficient of viscosity. As the effect of surface tension,

$$\frac{\partial p}{\partial x_j} = -\sigma\frac{\partial}{\partial x_j}(\frac{1}{r}) \tag{4}$$

$\sigma$is the coefficient of surface tension, r is radius, According to equation (3) and (4), the momentum equation of mixed fluid is

$$\frac{\partial}{\partial t}\rho u_j + \frac{\partial}{\partial x_j}\rho u_i u_j = \sigma\frac{\partial}{\partial x_j}(\frac{1}{R}) + \mu\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \rho g_j \tag{5}$$

2.2. Numerical model of the tank

In this paper, the vane type tank shown in figure 1 mainly comprises of inside and outside blade which are both eight. The volume of tank is 4L, and the inside diameter is 170mm. These blades are used for transferring and storing propellant.

According to the model of the tank, the mesh of the tank is divided using block hexahedron gird method. In order to mesh the tank simply, the 1/8 tank is divided into three parts. The grid numbers of the model is 2.3 million. The numerical model of the tank is shown in figure 2.

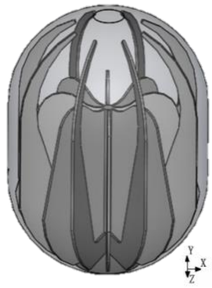


Figure 1. The model of the tank.

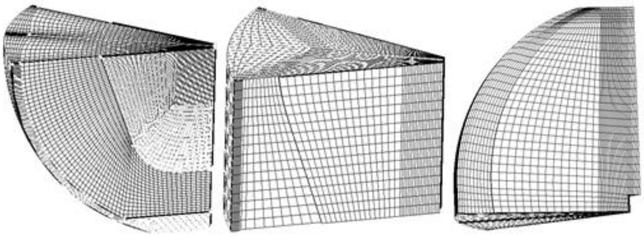


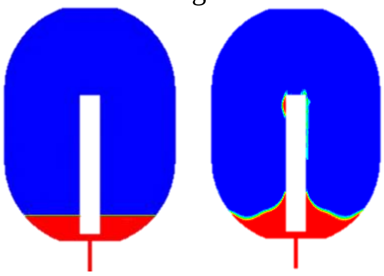
Figure 2. The mesh of the tank.

The commercial CFD code FLUENT is used to perform the simulations. The boundary conditions of all the walls are set to solid wall. The outlet is set to pressure-outlet and the inlet is set to velocity-inlet. The computational domain includes liquid and gas. The first phase is set to liquid which is MMH, and the second phase is set to gas which is air. In this paper, the reorientation process with filling ratio 5%, 40%, 60% are simulated, while the microgravity acceleration is 1×10^{-5} g and the direction is for -Y. The reorientation process with filling ratio 5% and 60% are simulated, while the microgravity acceleration is 1×10^{-3} g and the direction is for +X.

2.3. Result of numerical simulation

The reorientation process with filling ratio 5%, 40% and 60% are simulated to adequately research the characteristic of the tank PMD, while the microgravity acceleration is 1×10^{-5} g and the direction is for -Y. The fluid distributions are shown in figure 3, 4, and 5. The blue color is gas, the red color is liquid.

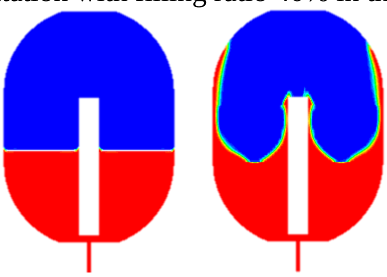
Figure 3 shows the fluid reorientation with filling ratio 5% in the tank.



t=0s t=10s

Fig.3 Fluid reorientation in the tank with filling ratio 5%

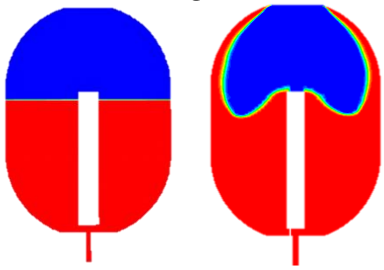
Figure 4 shows the fluid reorientation with filling ratio 40% in the tank.



t=0s t=10s

Fig.4 Fluid reorientation in the tank with fill ratio 40%

Figure 5 shows the fluid reorientation with filling ratio 60% in the tank.



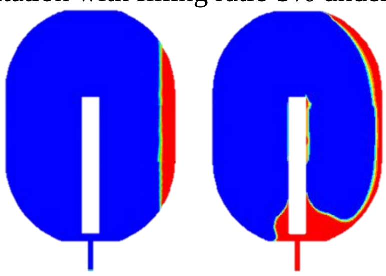
t=0s t=10s

Fig.5 Fluid reorientation in the tank with fill ratio 60%

Seeing from the figure 3, 4 and 5, in microgravity environment, the liquid flow along the inside and outside vanes due to the force of surface tension, and the height of the liquid could reach the top of the blade column. Gas and liquid is without mixing in the process of reorientation, and concave surface is formed between the blades. In the end, the liquid position around the PMD in the tank to cover the liquid outlet, and the gas position in the top of the tank. The result indicates that the vane type PMD can availably achieve the separation between liquid and gas interface and providing liquid without gas to thrusters, while the microgravity acceleration is 1×10^{-5} g and the direction is for -Y.

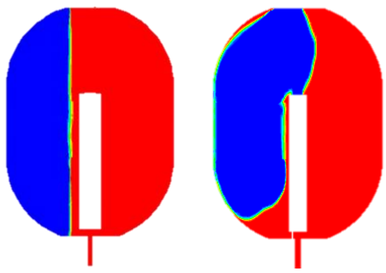
The reorientation process with filling ratio 5% and 60% are simulated to adequately research the characteristic of the tank PMD, while the microgravity acceleration is 1×10^{-3} g and the direction is for +X. The fluid distributions are shown in figure 6 and 7.

Figure 6 shows the fluid reorientation with filling ratio 5% under lateral microgravity acceleration.



t=0s t=18s

Fig.6 Fluid reorientation in the tank with fill ratio 5% under lateral microgravity acceleration



t=0s t=18s

Fig.7 Fluid reorientation in the tank with fill ratio 60% under lateral microgravity acceleration

Seeing from the figure 6 and 7, in the microgravity acceleration which is 1×10^{-3} g and the direction is for +X, the liquid flow along the vanes. Gas and liquid is without mixing in the process of reorientation. In the end, the liquid position around the PMD in the tank to cover the liquid outlet. The result indicates that the vane type PMD can availably achieve the separation between liquid and gas interface and providing liquid without gas to thruster, while the microgravity acceleration is 1×10^{-5} g and the direction is for -Y.

3. Microgravity test

3.1. Test system

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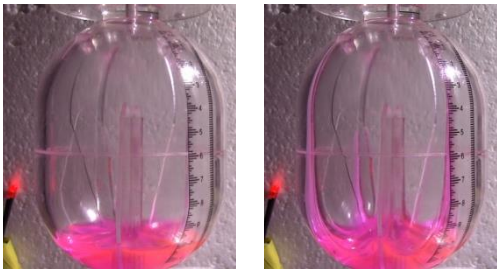
Microgravity drop tower tests which are most usual in the means of microgravity tests can provide short microgravity time, but can supply relatively low microgravity level. In the paper, the microgravity tests have been carried out in the hundred meters drop tower of the National Microgravity Laboratory. 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 equipment and so on. According to the requirement of microgravity drop tower experiment research, the test system is built, which consists of abbreviate models, the test bracket, the lighting device and the picture acquisition device and so on. In the system, the high resolution camera with CCD is using for recording fluid climbing process, distribution and reorientation process in abbreviate models.

3.2. Result of the test

In the test, the drop tower experiments with filling ratio 5%, 40% and 60% in the tank which is in forward direction have been carried out. The fluid distributions are shown in figure 8,9 and 10.

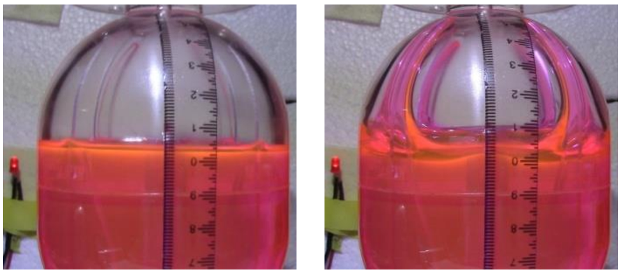


t=0s t=3s

Figure 8. Fluid reorientation with filling ratio 5% in forward direction.

t=0s t=3s

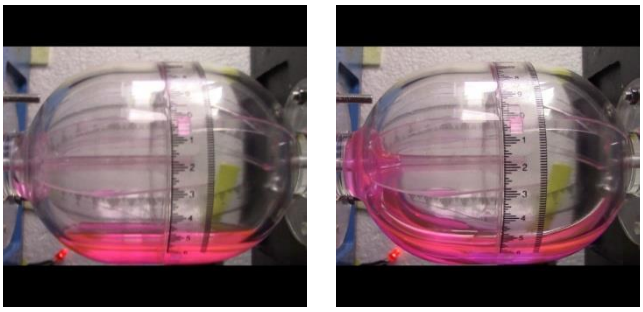
Figure 9. Fluid reorientation with filling ratio 40% in forward direction.



t=0s t=3s

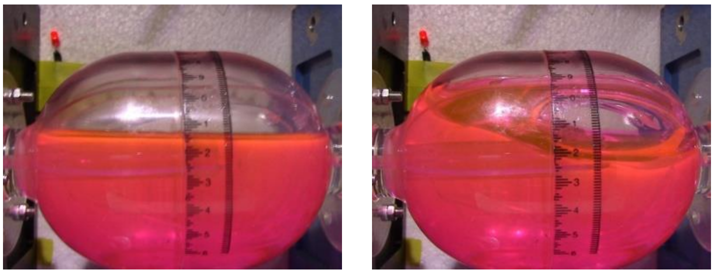
Figure 10. Fluid reorientation with filling ratio 60% in forward direction.

The drop tower experiments with filling ratio 5% and 60% in the tank which is in lateral direction have been carried out. The fluid distributions are shown in figure 11 and 12.



t=0s t=3s

Figure 11. Fluid reorientation with filling ratio 5% in lateral direction.



t=0s t=3s

Figure 12. Fluid reorientation with filling ratio 60% in lateral direction.

Seeing from these figures, in the drop tower experiments, by using of surface tension, the fluid rapid climb along the tap region between vanes and inner walls of the tank. And a concave liquid surface between vanes and inner walls is shaped under microgravity environment. The liquid mainly reserves in the bottom of tank and the region between vanes and inner walls and covers the liquid outlet of the tank. The experiment results indicate that the vane type tank has good and initiative fluid orbital management ability and can availably separate between fluid and gas, and provide propellant without gas for thrusters.

4. Conclusion

Numerical simulation and experiment of the flow in vane type with microgravity have been carried out. The fluid distributing rule has been obtained. The results from numerical simulation are in good agreement with ones from the microgravity drop tower tests. The results indicate that the PMD of the vane type tank can availably achieve the separation between liquid and gas interface and providing liquid without gas. Gas and liquid is without mixing in the process of reorientation. The liquid positioned around the PMD in the tank to cover the liquid outlet, and the gas positioned in the top of the tank. The vane type tank has good performance of propellant management in microgravity environment.

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