

Numerical simulation of fluid flow in the vane type tank on orbital refuelling process

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Abstract: On-orbit refuelling of spacecraft is one of the main on-orbit service modes, which is the main technical means to increase the working life and improve the economic efficiency of the spacecraft. The vane type tank is one of the most advanced tanks, which can manage all of the propellant. The vane device is the form of propellant management for the low-gravity expulsion of propellant from spacecraft. The orbital propellant management is achieved by the vane type propellant tank. The fluid reorientation and refilling in space environment is the key technology of on-orbit refuelling. However, 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 on-orbit refueling. Focusing on the research of the vane type tank of on-orbit refueling, by using a VOF two-phase flow model, the fluid behavior in microgravity environment and the flow characteristic of the refueling process in tank is numerically simulated to research the performance of the vane type tank.

1. Introduction

On-orbit refueling of spacecraft is one of the main on-orbit service modes, which is the main technical means to increase the working life and improve the economic efficiency of the spacecraft. On-orbit refueling is one of the trends in space technology. At present, many countries have studied the technology of on-orbit refueling, such as America and Russia. On-orbit refueling based on vane type tank using the transfer pump is one of the trends in on-orbit refueling technology, and the vane type tank is the foundation. The principal advantages of the vanes type tank are weight, reliability, 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. The study of the fluid behavior in microgravity environment is crucial. However, 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 on-orbit refueling. In this paper, by using a VOF two-phase flow model, the fluid behavior in microgravity environment and the flow characteristic of the refueling process in tank are numerically simulated to research the performance of the vane type tank.

2. Numerical model

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. 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.

$$\rho = \alpha_1 \rho_1 + \alpha_2 \rho_2, \quad \alpha_1 + \alpha_2 = 1 \quad (2.1)$$

ρ is the density of mixed fluid, α_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

$$\frac{\partial}{\partial t}(\rho) + \frac{\partial}{\partial x_i}(\rho u_i) = R \quad (2.2)$$

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

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

$$\frac{\partial}{\partial t} \rho u_j + \frac{\partial}{\partial x_j} \rho u_i u_j = -\frac{\partial p}{\partial x_j} + \mu \frac{\partial}{\partial x_j} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \rho g_j \quad (2.3)$$

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,

$$\frac{\partial p}{\partial x_j} = -\sigma \frac{\partial}{\partial x_j} \left(\frac{1}{r} \right) \quad (2.4)$$

σ is the coefficient of surface tension, r is radius, According to equation (2.3) and (2.4), the momentum equation of mixed fluid is

$$\frac{\partial}{\partial t} \rho u_j + \frac{\partial}{\partial x_j} \rho u_i u_j = \sigma \frac{\partial}{\partial x_j} \left(\frac{1}{R} \right) + \mu \frac{\partial}{\partial x_j} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \rho g_j \quad (2.5)$$

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.

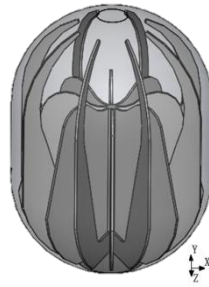


Figure 1.The model of the tank

According to the model of the tank, the mesh of the tank is divided using block hexahedron grid 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.

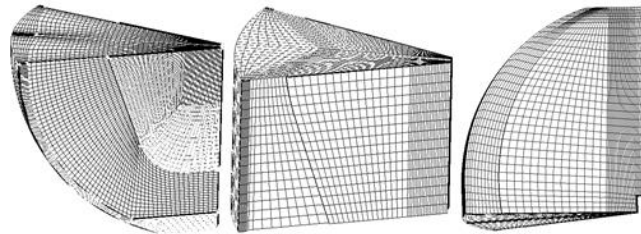


Figure 2.The mesh of the tank

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%, 50% and 95% are simulated to adequately research the characteristic of the tank PMD. In the filling simulation, according to the actual situation of on-orbit refueling, the filling process of the tank from 5% to 95% is simulated.

3. Result and discussion

3.1. The simulation of reorientation in microgravity acceleration

The reorientation process with filling ratio 5%, 50% and 95% are simulated to adequately research the characteristic of the tank PMD. The microgravity acceleration under fluid-sinking mode is $1 \times 10^{-5} g$. 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.

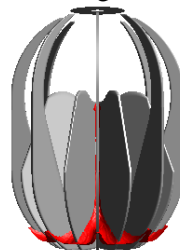


Figure 3. Fluid reorientation in the tank with filling ratio 5%

Figure 4 shows the fluid reorientation with filling ratio 50% in the tank.

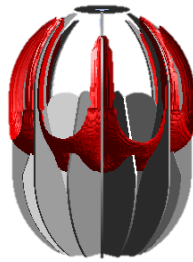


Figure 4. Fluid reorientation in the tank with fill ratio 50%

Figure 5 shows the fluid reorientation with filling ratio 95% in the tank.

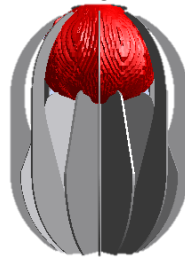


Figure 5. Fluid reorientation in the tank with fill ratio 95%

Seeing from these figures, 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. The height of the liquid along the outside vanes is higher than the inside vanes. The interface on the blades is higher than 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 thruster.

3.2. The simulation of filling in microgravity acceleration

In order to research the flow characteristic of the refueling process in tank, the filling process of the tank from 5% to 95% is simulated. The microgravity acceleration under fluid-sinking mode is $1 \times 10^{-5} g$. In the beginning, the filling ration of the tanks is 95% and 5%. The flow rate of filling is 1 L/min constantly. The pressure is constant in the process of filling. The process of filling is shown in figure 6.

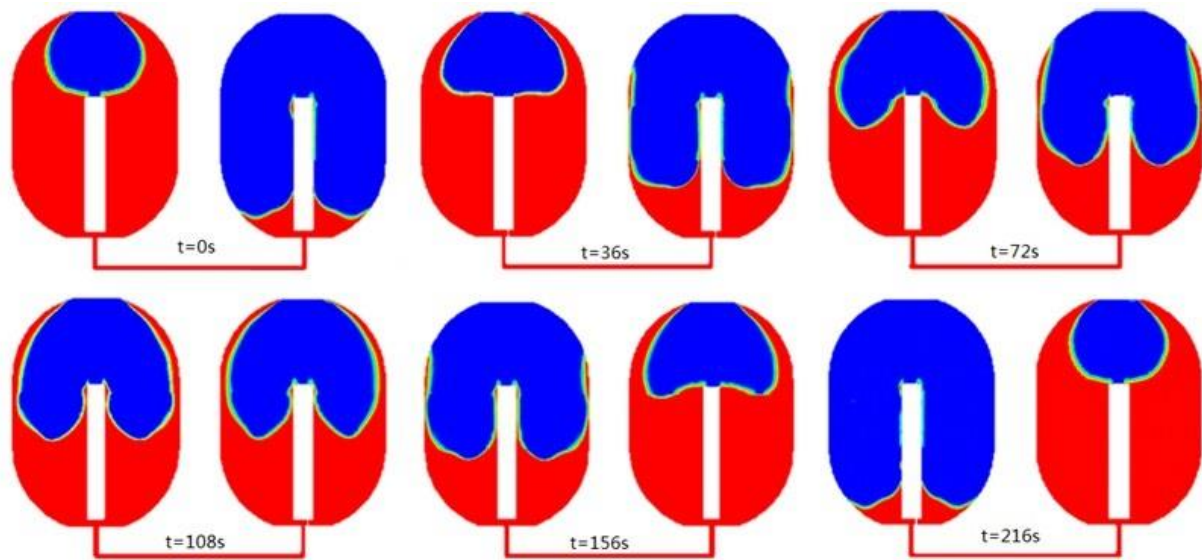


Figure 6. Distribution of the gas-fluid interface in refueling

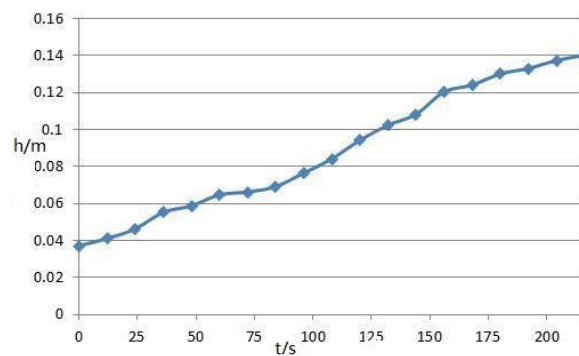


Figure 7. Variation of the center of mass of the receive tank

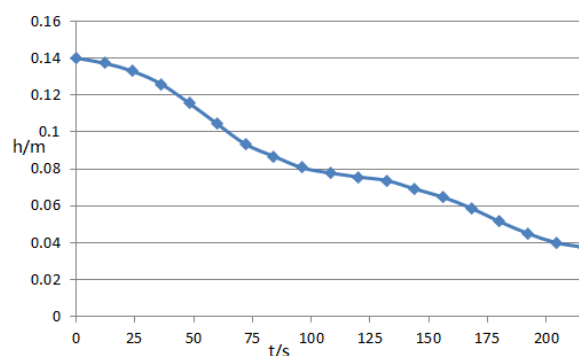


Figure 8. Variation of the center of mass of the transfer tank

Figure 6 shows the distribution of the gas-fluid interface in refueling. The left tank is transfer tank, and the right tank is receive tank. In the process of refueling, the separation between gas and liquid interface is stable clearly. The liquid position around the PMD in the tank to cover the liquid outlet, and the gas position in the top of the tank to cover the gas outlet. The result indicates that the vane type PMD has good fluid orbital management ability. Figure 7 shows the variation of the center of mass of the receive tank. Figure 8 shows the variation of the center of mass of the transfer tank. In

transfer tank, the center of mass decreases from 0.14 m to 0.04m, as the filling ratio from 95% to 5%. In receive tank, the center of mass increases from 0.04 m to 0.14m, as the filling ratio from 5% to 95%.

4. Conclusion

Numerical simulations of the flow in the tank with microgravity have been carried out. Gas and liquid are 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 results indicate that the PMD of the vane type tank can available achieve the separation between liquid and gas interface and providing liquid without gas. The flow characteristic of the fueling process in tank is numerically simulated. The results indicate that the vane type PMD has good fluid orbital management ability. The vane type tank can be used in on-orbit refueling.

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