Numerical simulation of the vane type tank and system on-orbit refueling process

Lei Chen¹,²,³, Jintao Liu¹,², Xinrong Lin¹,², Can Yao¹,² and Honglai Zhu¹,²

¹ Beijing Institute of Control Engineering, Beijing, 100190, China
² Beijing Engineering Research Center of Efficient and Green Aerospace Propulsion Technology, Beijing, 100190, China
³ E-mail: chenlei1340@126.com

Abstract. The orbital propellant management achieved by the vane type propellant tank is presented in this paper. Focusing on the research of the vane type tank of on-orbit refueling, by using a VOF (volume of fluid) two-phase flow model, the fluid behavior in microgravity environment and the flow characteristic of the refueling process in tank is numerically simulated. The fluid distributing rule is obtained. By using the system simulation software AMESim, a simulation system for orbital refueling is designed, and the refueling process is simulated on the system. The results of numerical simulation of the vane type tank and system indicate that the orbital refueling is feasible.

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 [1~3]. 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 [4~6]. 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 van type tank. By using the system simulation software AMESim, a simulation system for orbital refueling which is a experimental platform of vane type tank is designed, and the refueling process is simulated on the system. The results of numerical simulation of the vane type tank and system indicate that the orbital refueling is feasible.

2. Numerical simulation of the vane type tank

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.

\[
\rho = \alpha_1 \rho_1 + \alpha_2 \rho_2, \quad \alpha_1 + \alpha_2 = 1
\]  

\(\rho\) is the density of mixed fluid, \(\alpha_1\) and \(\alpha_2\) are the volume fractions of the two phase, \(\rho_1\) and \(\rho_2\) are the densities of the two phase, which are given values.

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

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

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

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

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

\(p\) 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 \(\mu\) is coefficient of viscosity. As the effect of surface tension,

\[
\frac{\partial p}{\partial x_j} = -\sigma \frac{\partial}{\partial x_j} \left( \frac{1}{r} \right)
\]

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

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

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.
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, according to the actual situation of on-orbit refueling, the filling process of the tank from 5% to 95% is simulated.

2.3. Result of 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 $1 \times 10^{-5} \text{g}$. 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 3.

Figure 4 shows the distribution of the gas-fluid interface in refueling. The left tank is transfer tank, and the right tank is received tank. In the process of refueling, the separation between gas and liquid
interface is stable clearly. The liquid is around the PMD and the gas is in the top of the tank. The result indicates that the vane type PMD has good fluid orbital management ability. Figure 5 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%.

![Figure 4](image1.png)

**Figure 4.** Variation of the center of mass of the receive tank.

![Figure 5](image2.png)

**Figure 5.** Variation of the center of mass of the transfer tank.

3. **Numerical simulation of the system**

In order to verify the feasibility and rationality of on-orbit refueling, a simulation system for orbital refueling is designed by using the system simulation software AMESim. The relationship between the filling pressure, the discharge pressure and the rate of flow is obtained.

3.1. **The structure of the system**

The system consists of transfer tank, receive tank, constant pressure cylinder, pressure sensor, pipeline and so on. The numerical system is shown in figure 6. In the system, gas is set for helium, and propellant is set for MMH. The filling ration of the tanks is 95% and 5%. The pressure of transfer tank and constant pressure cylinder is 0.2MPa, and the pressure of receive tank is 0.16MPa.
3.2. Result of the simulation of the system
In the test, the cylinder supplies the transfer tank with gas. Due to the differential pressure, the propellant flow from the transfer tank to the receive tank. The pressure of the receive tank is reduced while the pressure exceeds the set point. When the pressure of the receive tank drop to 0.15MPa, the pressure relief valve is closed. The process is circular, until the filling is complete. More and more propellant of the receive tank, the pressure of the system changes faster and faster. The pressure, propellant quality and filling ration of the receive tank is shown in figure 7, 8, 9.
4. Conclusions

Numerical simulate of the flow characteristic of the fueling process in tank have been carried out. The result indicates that the PMD of the vane type tank can availabley achieve the separation between liquid and gas interface and providing liquid without gas. The vane type PMD has good fluid orbital management ability. The vane type tank can be used in on-orbit refueling. The characteristic of the system for orbital refueling is numerically simulated. The relationship between the filling pressure, the discharge pressure and the rate of flow is obtained. The result indicates that the system for orbital refueling is feasible.

References
[1] Dipprey N F and Rotenberger S J 2003 Orbital express propellant resupply servicing The 39th Joint Propulsion Conference and Exhibit (2003)20-23
[2] JaekleJr D E 1991 Propellant management device conceptual design and analysis: vanes The 27th Joint Propulsion Conf. (1991)24-26
[3] Hu Q, Li Y, et al.2013 Aero Control and Application. 39(3) 58-62
[4] S. Dominick and J. Tegart 1994 Orbital Test Results of a vaned Liquid Acquisition Device The 30th AIAA Joint Propulsion Conference and Exhibit (1994) 27-29
[5] David J C and Timothy A M 1997 Vented Tank Resupply Experiment - Flight Test Results The 33rd Joint Propulsion Conference and Exhibit (1997) 6-9
[6] Zhuang B T, Li Y, et al. 2014 Aero Control and Application 40(1) 27-30
[7] Sharipov F and Kalempa D 2002 Gaseous Mixture Flow through a Long Tube at Arbitrary Knudsen Numbers Journal of Vacuum Science and Technology 20(3)814-822.
[8] Hirt C W Nichols B D 1981 Volume of fluid (VOF) method for the dynamics of free boundaries Journal of Computational Physics 39 201-225
[9] Tsai W, Yue D K 1996 Computation of Nonlinear Free-Surface Flows Annual Review of Fluid Mechanics 28 249-278
[10] Shin S and Lee W I 2000 Finite element analysis of incompressible viscous flow with moving free surface by selective volume of fluid method International Journal of Heat and Fluid Flow 21 197-206