Experimental study on liquid distribution in a vane type propellant tank

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Abstract. Propellant tank is used to store the propellant in propulsion system. Propellant management device (PMD) is the key component in propellant tank to manage the liquid propellant under zero gravity. A microgravity drop tower test system was established to investigate the performance of PMD. A kind of vane type propellant tank was used for the drop tower test. Single module was used for experiment tests, and the microgravity level was between $10^{-2}g_0$ and $10^{-3}g_0$. The anhydrous ethanol is used as analogue liquid. Different volume fraction of liquid were used to study influence of the PMD on the management performance. Changes of gas-liquid interface during the test are studied. Velocities flow along the vane of different liquid volume fraction in the tank are different at the beginning ($t<0.8s$). The liquid reorientation time is 0.8s when the liquid volume fraction is larger than 10%. The liquid reorientation time is prolong when the liquid volume fraction is less than 10%. The liquid climbing height along vane under microgravity increases as the volume fraction of liquid reduces. Experimental results provide a favorable reference for further optimization design of vane type propellant tank.

1. Introduction

For liquid propulsion of satellite, propellant tank is used to store the propellant. The tank is more complex, needing to manage the liquid propellant under zero gravity to ensure that liquid, rather than gas, is expelled from the tank. Gravity affects many processes in space, such as the separation of the liquid and gas phases within a propellant tank [1]. To meet gas-free transfer requirements for propellant system in satellite, propellant management device (PMD) may be required inside the tank[2]. PMD must be designed and implemented to ensure that there is always communication between the PMD and liquid anywhere within the tank and to ensure that the tank outlet is sufficiently covered with liquid during any phase of the mission[3]. Vane type tank is a kind of new generation surface tension propellant tanks, and there is no screen inside this kind of tank. The PMD of vane type tank is composed by vane, refillable reservoir and other components[4]. The liquid inside the vane type tank is driven by the capillary force to the output of the tank.

Relative to screen channel liquid acquisition devices (LAD), vanes are open acquisition PMDs. Vanes are generally designed as thin metal plates that are mounted parallel or perpendicular to the tank walls. Vanes are sized and numbered so that there is always communication between the propellant and vane[5-6]. Vanes are particularly beneficial in satellite systems requiring periodic station-keeping maneuvers because satellites only require occasional access to propellant over the course of a long-duration mission[7]. The lightweight vane is also ideal to reduce the weight of the propellant tank. Vanes are the key component of a propellant tank. The vane design process starts with the evaluation of the
mission requirements to determine whether vanes are suitable [8-10]. Once suitability is established, the design configuration and the design details must be evaluated by numerical or experimental investigation[11].

There were only three experiments that employed a vane-type PMD in space so far due to the expensive cost[12]. The first experiment was performed in the Fluid Acquisition Resupply Experiment-II (FARE-II) project, and tested a performance of vane using a simulant fluid onboard the shuttle mission STS-57 as its primary PMD[13]. The purpose of the experiment was to evaluate vane performance limits in terms of maximum achievable expulsion efficiencies under adverse acceleration levels[14]. The second experiment was performed in the Vented Tank Resupply Experiment (VTRE) project. The performance of a vane-type PMD was tested onboard the shuttle mission STS-77[15]. Twelve outer and 12 inner vanes were mounted inside a small-scale plexiglass tank so that the liquid distribution in the tank can be seen clearly [16]. The third experiment was performed in on-orbit filling project. A 4 liter with vane type PMD was sent into space by rocket CZ-7[17].

The most universal way to evaluate the performance of a vane type PMD is drop tower test. Rui[18] used a sphere scale vane tank to study the liquid-gas interface behaviors with different acceleration vector and different filling independently. A series of stable equilibrium interface and relocation time was obtained. Bolleddula [19] investigated the capillary flow phenomena using drop towers, and made a conclusion that compound capillary flows occurred spontaneously and simultaneously over local and global length scales. Li[20] studied capillary flow in asymmetry interior corner in the vane-type surface tension tank. Zhuang[21] performed an experiment on fluid storage characteristic of refillable reservoir in microgravity. Kang[22] investigated the fluid-gas interface in a vane type surface tension tank by drop tower test.

In this paper, a microgravity drop tower test system was established. Different liquid volume fraction were used to study the influence of the PMD on the liquid transport performance. Experiment tests were also performed with different direction of gravity.

2. Drop tower test system

Microgravity drop tower tests which can set up low microgravity environment with short time. Experiment tests of vanes and refillable reservoir in microgravity were carried out in the drop tower of National Microgravity Laboratory (NML)[8]. The NML free falling tower can keep microgravity condition in 3.5s. The drop tower test system is shown in Fig.1, which is composed of experiment module, deceleration recovery system, release system, control system, measurement system and auxiliary facilities. The experiment module is the key component of the system, and it can provide microgravity environment during fall drop process. The experiment module is divided into two types, which are double module and single module. For double module, the space between the internal module and outer module can be pumped vacuum. The internal module also free fall drop in the outer module. There has no resistance for the internal module during the fall drop process. Double module can provide microgravity between $10^{-4}g_0$ and $10^{-5}g_0$. $g_0$ is the ground gravity. For single module, the microgravity level is between $10^{-2}g_0$ and $10^{-3}g_0$. Single or double module can be used separately according to the needs of experimental microgravity level. According to the requirement of microgravity, single module is used for experiment tests of vanes and refillable reservoir.

3. Test model

A new vane type propellant tank was chosen as research object, which is shown in Figure 2. Vanes and refillable reservoir are the main component of the PMD. The volume of the tank is 2 Liters. The tank have 4 large vanes. The diameter of the tank is 120 mm.

The vane and tank casing are made of plexiglas. The vane are fixed on the plexiglas casing, and paralleling to the container wall with a certain distance 3mm. The kinematic viscosity coefficient of anhydrous ethanol is $10.556\times10^{-4}$ Pa·s, and the contact angle between anhydrous ethanol and plexiglas is 0. Microgravity drop tower tests were carried out on different liquid volume fraction. The effects of volume fraction on liquid transfer velocity were studied.
1. release system, 2. experiment module, 3. deceleration recovery system, 4. control system

Figure 1 Drop tower test system

The vane type tank is fixed on the support which is shown in Figure 3. Experiment test with micro gravity can be performed by this fixture.

4. Experimental result

5 different liquid volume fraction are chosen for the drop tower test in vertical direction. Volume fractions are 3.5%, 25% and 60%. Experimental results are shown in Figure 4-6. At the beginning, anhydrous ethanol forms a curved concave gas-liquid interface due to the surface tension and static pressure balance formed by solid, liquid and gas in the gap. When the experimental model begins to drop, the gravity environment of the tank changes from 1g to $10^{-3}$g. At this time, the surface tension begins to play an important role. The initial balance of the liquid inside the tank is broken, and the surface is stretched along the vane inside the tank. Under the effect of surface tension, the liquid begins to flow. The liquid in the tank flows from the place with small curvature to the place with large curvature under the effect of pressure difference until the potential energy reaches the minimum. It can be seen that the liquid climbs up rapidly along the vane. After the liquid reaches the top, the liquid forms a stable gas-liquid interface.
Figure 4 Liquid volume fraction is 3.5%

Figure 5 Liquid volume fraction is 25%
Figure 6 Liquid volume fraction is 60%.

Figure 7 shows the climbing height during the drop test. Figure 8 shows the change of flow velocity along the vane inside the tank during the drop test. The liquid climbing height along vane under microgravity increases as the volume fraction of liquid reduces. Velocities flow along the vane of different liquid volume fraction in the tank are different at the beginning (t<0.8s). The liquid reorientation time is 0.8s when the liquid volume fraction is larger than 10%. The liquid reorientation time is prolonged when the liquid volume fraction is less than 10%. With the decrease of the liquid volume in the tank, the liquid in the tank will distribute along the space between the vane and the tank as far as possible. The liquid climbing height increases as well as the reorientation time is prolonged as the liquid volume fraction reduces. It can also be concluded that the flow velocity is close to about 0.02 m/s when volume fraction are less than 10, and close to about 0.015 m/s when volume fraction are more than 10%.

5. Conclusions

A new vane type propellant tank were experimental studied by drop tower test. The liquid climbing height along vane under microgravity increases as the volume fraction of liquid reduces. The liquid reorientation time is 0.8s when the liquid volume fraction is larger than 10%. The liquid reorientation
time is prolonged to 1.7s when the liquid volume fraction is 3.5%. The liquid climbing height increases as well as the reorientation time is prolonged as the liquid volume fraction reduces. Most of the liquid is collected at the outlet of the tank to meet the requirement of the thruster. It should be ensured that the liquid can be smoothly discharged at the end of life for the design of refillable reservoir.

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