The Numerical Analysis to Gas-Liquid Separator used in On-orbit Refuelling Mission

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Abstract. In the process of on-orbit refuel, the gas-liquid separator needs to separate the pressurized gas from the propellant, and discharges the gas out of the tank in the process of the tank refilling by propellant. In this paper, the gas-liquid separator has been developed, which could effectively separate the gas-liquid under microgravity conditions. The numerical analysis result shown that the stability of gas-liquid separation was the key characteristics, which was closely related to the geometric parameters of the fluid domain.

1. Introduction

The on-orbit refueling technology of satellite propellant is the key technology to extend the working life of satellite and greatly reduce the cost of satellite. Under microgravity condition, the effective separation the pressurized gas from the propellant is the key technology to achieving the mission of on-orbit refuel of satellite. The process is accomplished by a gas-liquid separator, which needs to separate the pressurized gas from the propellant, and discharges the gas out of the tank in the process of the tank refilling by propellant. The gas-liquid separator involved in this study has been developed based on static gas-liquid separation technology, which was designed based on the surface tension and centrifugal force. The gas-liquid separator has no moving parts, low energy consumption, no maintenance, reliable separation, easy control and other characteristics.

2. The mechanism of gas-liquid separator

2.1. Static gas-liquid separation technology

Static gas-liquid separation technology includes the following three technical approaches [1]: (1) Capillarity gas-liquid separation technology is mainly based on the characteristics of hydrophilic/hydrophobic materials and the capillary effect generated by surface tension. (2) The cyclone gas-liquid separation technology is mainly based on the centrifugal effect of the gas-liquid mixed fluid flowing through the vortex pipeline. (3) Inertial gas-liquid separation technology is mainly based on the principle that the inertia of gas and liquid is very different, and the liquid is not easy to change the direction of motion and is collected by hydrophilic film.

2.2. The mechanism of gas-liquid separator

Based on the above three typical gas-liquid separation technologies, Weislogel [2] proposed a device to solve the problem of static gas-liquid separation on a spacecraft. The operating principle of the device is shown in figure 1. The main body of the device is a spiral tube structure similar to the "ice cream cone section", which consists of three sections, including the inlet section A-A, the diffusion section B-B, the passive capillary separation section and the liquid collection section C-C [3].
Regardless of whether the gas-liquid phase enters the ice cream cone section A-A in any form, the liquid adheres to the internal surface of the device and slows down rapidly, thus being driven downstream by the gas [4]. The function of the tapered section is to guide the large contact angle of the liquid to the bottom sequentially. Once the liquid has accumulated here, the flow will become stable and will not change its flow state even if it enters the straight section again.

The centrifugal flow track mainly provides the following functions: (1) It is used to provide a driving force to make free droplets adhere to the dry wall when they hit it or combine with other liquid surfaces. (2) By accumulating the liquid to the apex of the tapered duct, it is easy to drive the air downstream to the liquid collection section C-C without sufficient capillary force due to poor wettability. (3) The results of flight experiments show that when free droplets come into contact with the previously adhered liquid surface, aggregation effect may not always occur. It is possible that free droplets will rebound from the liquid surface, and even aggregation may form free flow. Therefore, the liquid must be accumulated to the bottom of the conical section by a certain centrifugal acceleration. Based on the statistical law, the shortest length of the spiral pipe can be preliminarily determined to realize gas-liquid separation at a given gas velocity.

C-C section guide vane structure mainly provides the following functions: (1) For a liquid with poor wettability, it can be drained to a designated position by the guide vane structure and dragged downstream by the gas in the flow path. In this way, the guide vane provides capillarity and thus gathers the liquid together to facilitate the discharge of the liquid to the outlet. (2) Along the fluid flow path, the effective area and density of the guide vane is changed to provide a better opportunity for the droplet to adhere to the guide vane and to polymerize with a droplet that may already exist at that location. (3) The Angle of the inner guide vane of the guide vane structure decreases continuously along the flow direction, providing a passive way to suck the trapped gas out of the liquid during the downstream movement. The fluid domains between the guide vanes are interconnected, and large liquid substances are removed through a single, larger liquid outlet at the bottom of the conical section, which will not be prone to blockage over time due to pollution.

### 3. Simulation of gas-liquid separator

#### 3.1. The structure design and fluid domain

According to the function and index requirements of the in-orbit refueling mission, the gas-liquid separator is designed based on the mechanism described above. The index requirements of gas-liquid separator are as follows: flow rate is 10L/min; volume proportion of liquid is 10%. Therefore the main parameters of the gas-liquid separator are as follows: the diameter of the spiral section is 6.35mm, the cone angle is 40 °, the inner diameter of the spiral is 76.2mm, the outer diameter is 101mm; the diameter of the collection section is 14.4mm, the cone angle is 40 ° and the length is 106mm, and the included angle of the three internal guide vane is 15 °. The fluid domain is shown in Figure 3, and the internal guide vanes is shown in Figure 4.
3.2. Calculation model of gas-liquid separator

According to the structure characteristics of gas-liquid separator, the fluid calculation domain is divided into two parts: spiral separation section and collection section. The calculation domain is meshed by ICEM software, in which hexahedral grid is used for spiral separation section as shown in Figure 5, and tetrahedral grid is used for collection section as shown in Figure 6.

ANSYS-CFX software is selected as the solver [5]. Because the gas-liquid separation process has very strong unsteady characteristics, the unsteady transient multiphase flow simulation is adopted, and the K-ε model is selected as the turbulence model. The gas is ideal helium, which is set as continuous phase, and the liquid is deionized water. As the volume fraction of liquid in this project is less than 10%, it is set as discrete phase, with solid-liquid surface tension coefficient of 0.072n/m and contact angle of 5°. In the initial calculation, the rated flow at the inlet is 10L/min, the volume fraction of liquid is 10%, and the time step is 0.001s.

3.3. Calculation results of gas-liquid separator

In order to evaluate the gas-liquid separation effect of gas-liquid separator, the gas ratio escaping from the liquid outlet and the liquid ratio escaping from the gas outlet are mainly monitored in the calculation process. In CFX, the gas ratio \( \xi_{\text{air}} \) escaping from the liquid outlet is defined as equation (1), and the liquid ratio \( \xi_{\text{water}} \) escaping from the gas outlet is defined as equation (2):

\[
\xi_{\text{air}} = \frac{\text{abs( Air.massFlow()@Fluid Outlet/ Air.massFlow()@Inlet)}}{1}
\]

\[
\xi_{\text{water}} = \frac{\text{abs( Fluid 1.massFlow()@Air Outlet/ Fluid 1.massFlow()@Inlet)}}{1}
\]

For the initial gas-liquid separator structure designed above, its gas-liquid separation rate is shown in Figure 7. It can be seen that after 2 seconds, the liquid basically fills the cone top area of the collection section and flows out to the gas outlet intermittently. In addition, since the liquid outlet section is well sealed by the liquid, the rate of gas escaping from the liquid outlet after 1.5 seconds is low.

In order to show the two-phase flow pattern in gas-liquid separator more intuitively, the evolution process of gas-liquid two-phase flow in gas-liquid separator structure is shown in Figure 8. It can be clearly seen from the figure that due to the capillary action and centrifugal force of the conical structure, most of the liquid components (red part) accumulate at the top of the conical section. At the same time,
due to the drag effect of the gas, when the liquid accumulates at the top of the cone of the collection section, a small amount of liquid accumulates at the left end and then overflows from the gas outlet, which is also the main reason for the fluctuating peak of the liquid separation rate in Figure 7.

4. Conclusions
The results of analysis indicates that the gas-liquid separator could effectively separate gas-liquid mixture under microgravity conditions, therefore it would effectively solve the problem of gas-liquid separation of the tank gas-port in the orbital fuel resupply mission. However, the numerical calculation results has shown that the stability of gas-liquid separation was the key characteristics, which was closely related to the geometric parameters of the fluid domain. It is necessary to optimize the parameters of the fluid domain in future.

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