博士論文(要約)

Experimental study of the multiphase flow inside water thrusters for microspacecraft

(水を推進剤とする小型宇宙推進機内部における多相流れの実験的研究)

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1 Introduction

In recent years, the number of launched small spacecraft has been expanding with unexpected speed. One of the reasons for the growth of the small satellite market is the development of microelectronics systems and space technologies that are lighter, smaller, and cheaper, yet equally or more functional. Although the primary purpose of nano/microspacecraft still has been technology demonstration, their use has also been rapidly expanding in recent years. Propulsion systems are essential for the sophisticated missions. A lot of micro propulsion systems have been developed, and some of them have already been demonstrated in orbit.

The most important aspect of the propulsion system is the selection of its propellant. Safety and performance are the major criteria for propellant selection. In particular, for the microspacecraft, low hazardousness and small structural mass are of equal or greater importance than performance. Water is one of the most promising propellants with safety and high density. This section describes the current status and the potential problem of the water propulsion system.

One of the critical issues of water thruster is the limitation in the thrust-to-power ratio. In order to achieve the water propulsion system with a high thrust-to-power ratio, it is necessary to obtain the characteristics of the following physical phenomena.

1. To comprehend the vaporization process of liquid droplets under the room temperature vaporization and microgravity conditions by the observation of the visualized vaporization chamber (Chapter 2),
2. To articulate the characteristics of the water vapor flow inside the micronozzle by directly measuring the performance of the thruster (Chapter 3),
3. To investigate how and how much oxides are formed in the combustion field by measuring the ignition temperature of magnesium in bulk form and observing its combustion and generating oxides(Chapter 4).

This study carried out an experiment-based investigation for the above sub-objectives and found important suggestions from the engineering aspects.

2 Vaporization in Vaporization Chamber

The vaporization mechanism inside the vaporization chamber is important to estimate the performance of the propulsion system. Although a previous study assumed the droplet shape to be a hemisphere and the evaporation to occur through convective boiling, the measured performance was different from expected, suggesting that these assumptions are inappropriate. This chapter aims to observe the injected liquid behavior with vaporization in microgravity. During a drop tower experiment, gravity conditions of approximately 10^{-2}G were obtained for 1.4 s. The length of this period cannot cover the full duration of the droplet vaporization. Still, the main focus of the study is to investigate the state of the liquid during the short period immediately after the injection on the inner wall until the phenomenon settles down to a relatively steady state. Experiments under normal gravity were also carried out to investigate the effect of gravity on evaporation. In addition to the gravitational conditions, the surface roughness, injection mass, and wall temperature are important parameters for vaporization. The parameters are the following: the average wall surface roughness from 1.6 to 50 µm, the injection mass from approximately 60 to 350 mg, and the wall temperature from 14 to 22 °C.

The photographs during vaporization revealed that the injected liquid contacted the wall by the surface tension even under microgravity. The evaporation model was judged to be nucleate boiling in all cases. The size of the bubbles was larger under microgravity than that under normal gravity. The contact area of the liquid immediately after the injection was smaller under microgravity than under normal gravity. However, under microgravity, the contact area increased by the liquid scattering along with the large bubbles while boiling. One second after the start of the injection, the contact area under microgravity became almost the same as or larger than that under normal gravity.

The sensitivity analysis confirms that the pressure of the vaporization chamber increased with an increase in temperature. The results are consistent with previous studies on heat transfer upon nucleate boiling and support the claim that the temperature condition is under the critical heat flux point. The change in roughness effect was smaller under microgravity than under normal gravity. This occurred owing to the large bubble diameter and the low frequency of the bubble formation under microgravity.

3 Water Nozzle Performance

In supersonic nozzles, the gas adiabatically expands and accelerates. The temperature and pressure should decrease over the saturation curve in the process, especially for water vapor with a small boiling point. The vapor pressure decreases rapidly with decreasing temperature, down to or below the saturation pressure in the expansion area. In microthrusters such as MEMS thrusters, the Reynolds number of the nozzle flow inevitably becomes small. It is the viscosity of the flow that causes this decrease in performance, which has been widely studied not only in water vapor but also in many other gases. The nozzle efficiency, which is the ratio of measured thrust to the ideal one, has been studied. The trend of increasing efficiency with increasing Reynolds number is common to all. However, the thrust efficiency at low Reynolds numbers varies greatly, and the experimental values tend to be lower than the calculated ones.

The main objective of this chapter is to clarify the effects of Reynolds number and degree of supersaturation on water nozzle performance. The thrust of a micronozzle for a water resistojet thruster was directly measured while the mass flow rate and the temperature of the vapor were changed in the range of 2–10 mg/s and 290–400 K. As a result, the Reynolds number and degree of supersaturation at nozzle throat are 100–600 and −20–100 K, respectively. In micronozzle measurement, the facility effect, specifically the background pressure effect, must be considered. However, no quantitative relationship has been obtained over a wide range of Reynolds numbers and background pressures. Therefore, this study also evaluated the effect of changing the background pressure on the micronozzle performance. In order to eliminate the effect of condensation effect, argon was used as the fluid.

The measured discharge coefficient was approximately unity and did not depend on the Reynolds number. This behavior is different from that of the other gas propellants investigated (argon and nitrogen). One of the reasons for this is the increase in critical mass flux due to the two-phase nature of the flow in the case of water. The specific impulse efficiency depends on both the Reynolds number and the degree of superheating. It increases as the degree of superheating increases at small Reynolds numbers. However, this relationship does not hold at high Reynolds numbers. The numerical calculation implies that the Reynolds number can be attributed to the change in the degree of condensation of the flow. The viscosity may prevent the flow from expanding at small Reynolds numbers and reduce the condensation rate, but this does not occur at high Reynolds numbers.

Moreover, for a more accurate performance evaluation, this chapter also investigated how the background pressure affects the nozzle performance. The background pressure only affected the specific impulse efficiency, which suggested the flow would not be changed before the throat. The pressure effect on the specific impulse efficiency depends not only on the pressure ratio of the background to the inlet but also on the Reynolds number at the throat. The numerical simulation suggested that the plume diverged outside the nozzle, which caused a change in the pressure thrust. It was also confirmed that there was almost no effect of background pressure on the performance evaluation of the water nozzle, as inferred from this analysis.

4 Combustion of magnesium and water vapor

Metals, specifically aluminum and magnesium, have attracted widespread attention as fuels. Most of these researches pointed out the safety of the reactants and products. Furthermore, regarding performance, the theoretical volumetric specific impulse of a metal-water propellant is much higher than that of hydrazine, which is a chemical propellant conventionally used in a space propulsion system. Most aluminum/magnesium-water combustion studies have focused on nano/micron-sized particle combustion contained in composite solid propellants. However, these composite propellants degrade the safety and lack reignition capability. It is desirable that fuel and oxidizer are separately stored, considering the use for spacecraft. The best application of the metal fuel is in bulk form.

In order to realize the bulk-magnesium propulsion system, it is necessary to predict the ignition temperature quantitatively and to clarify the combustion efficiency and the state of the condensed combustion products produced. Most studies of magnesium-water reactions focus on premixing with powder or reaction in moist air . These combustion mechanisms are considered to be different from this study. In addition, it is clear that the state of the residual oxide changes with the oxidizer, and it is important to investigate this formation process.

This chapter focused on the chemical propulsion of magnesium and water to increase the thrust independent of the power limitation of the spacecraft. Since premixed powder-water propellants, which have been widely studied, are less safe and lose re-ignitability, the goal is to burn magnesium and water in a method that is stored separately and supplied to the propulsion system. However, there is a lack of knowledge on the combustion of magnesium and water, and further investigation is needed. The first objective of this chapter is to obtain the ignition temperature of wire-shaped magnesium and its dependency on the oxidizer pressure. The second is to observe how the condensed combustion products are generated in combustion flame. For the first purpose, a DC current heated a wire heating until it broke. The combustion limit temperature was determined by numerical analysis. Fuel was put on a plate heater to observe the combustion at the fixed view for the second purpose. The two-dimensional properties of condensed combustion particles in the combustion plume were obtained by measuring emission spectra and transmitted light. In this study, air and oxygen were also used as oxidizers to compare the results with water vapor.

The first half of this chapter study observed the ignition and combustion behavior of magnesium wire. A direct current heated a wire with 0.5 mm diameter under an oxidizing atmosphere of oxygen or water vapor. The oxidizer pressure was controlled in the range of 10–100 kPa. The heated wires were classified in two cases: combustion occurred and did not occur after breaking the wire. The classification and the break temperature, which was numerically calculated from the break timing, revealed that combustion would occur at high temperature or high oxidizer pressure, and there is a rough combustion limit in the experimental range. This limit can be considered to be the same as ignition temperature according to the thermal ignition theory. The obtained dependence of the ignition temperature on the oxidizer pressure was large compared with the previous studies, which can be understood from the balance between the significant heat diffusion and the Arrhenius-type reaction rate. Furthermore, it was found that the ignition temperature increased slightly in a water vapor atmosphere.

The latter experiment investigated the magnesium combustion plume by changing the oxidizer and its pressure. Two-color and light extinction measurements were applied to the field where the plate magnesium-based alloy, whose size is $5 \times 5 \times 0.5\ \mathrm{mm}^{-3}$, was burnt. Unlike the wire experiment, the fixed fuel enabled the investigation of the detailed mechanism of oxide formation and the state of the local combustion field. The change in the oxidizer caused a significant change in the appearance of the residual oxide. In the case of oxygen and air, most of the oxide was dispersed, but in the case of water vapor, much of the oxide remained near the fuel. The mass change before and after combustion was also consistent with this fact. The Lewis number can explain the reason for this difference. High Lewis numbers in the water experiment caused the small local combustion temperature, increasing the condensation of oxide particles near fuel. The two-dimensional temperature measurement confirmed the consideration. The spectroscopic measurement did not observe the MgO lines around 500 nm, suggesting that the gaseous magnesium oxide was not generated or immediately condensed. In addition, the surface oxidation before ignition was progressing in the water vapor case, which may be caused by the higher reaction speed on the surface and higher ignition temperature, as reported in the first experiment. The larger-scale surface oxide may enhance the accumulation of the condensed particle. There was a dependency of the oxide residue size on the oxidizer pressure. As the pressure decrease, the generated oxide residue became larger. The light extinction experiment also revealed that the condensed combustion products were widely presented in lower pressure experiments.

5 Practical Findings for Water Thrusters

The purpose of this chapter is to apply the knowledge obtained from the above studies to propulsion systems. First, the impact on thruster performance from the vaporizing mechanism was additionally considered. By assuming the conditions of the model case, the experimental result gave the following conclusions.

- The power input increased several times in microgravity from the nucleate boiling heat flux, suggesting that heat reuse is no longer effective in the conventional design.
- Two practical ways were considered to reuse more waste heat from the surroundings. One is to use more injection valves to increase the contact area. The other is to increase the conductance from the vaporization chamber to the vacuum to evaporate at a lower temperature.

Then, for the nozzle performance, the following methods are considered to improve the water thruster performance because the low Reynolds number effect did not arise or negligible in this region.

- A large throat diameter reduces input power when the mass flow rate is the same because the large conductance should enhance reusing waste heat.
- The effect of viscosity on the temperature change was negligible, indicating that the temperature increase directly increased the specific impulse rise and contributed to the increase in the thrust-to-power ratio.

Lastly, the following items were found to be necessary for the realization of the magnesium-water propulsion.

- Considering the spark ignition of 3W, which is the same ignition method in the previous study, it was found that the wire can reach the ignition temperature obtained in this study. The phenomenon that the ignition time became shorter with increasing pressure was also reproduced in the calculation.
- Dimensionless particle parameters in the nozzle frow were evaluated. It indicated that both the interaction between condensed particles and the volume fraction of the particles were negligible, and the particles would not follow the changes in the flow.
- Residual oxides may cause the thrust to drop down to about 10% from the ideal value. This problem would be solved by allowing the oxide to flow at about 10 m/s.