Numerical Study of Thermo-Fluid Dynamics Phenomena for Stable Operation of Loop Heat Pipes

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論文内容要約

Loop heat pipes (LHPs) are two-phase heat transfer devices developed in the Soviet Union in 1972 for the thermal control of spacecraft. An LHP consists of an evaporator, vapor line, condenser, liquid line, and reservoir. A porous medium called a wick is inserted in the evaporator and generates capillary force, which is the driving force of the LHP. This means that no external energy is required for the LHP to work. In addition, the LHP can transport a large amount of heat by evaporation and condensation of the working fluid. Because the vapor and liquid lines are smooth tubes, the LHP can transport heat over a longer distance than conventional heat pipes. As mentioned above, the LHP exhibits high heat transfer performance, and thus many spacecraft use LHPs for their thermal control systems. However, LHPs can exhibit unstable behaviors such as the failure of start-up, temperature oscillation, and temperature hysteresis. As the phenomena inside the LHP are very complex, these unstable behaviors have not been controlled yet. In this study, the internal phenomena of the LHP during the unstable behaviors were investigated by numerical simulation, with a particular focus on temperature oscillation and hysteresis. This thesis consists of five chapters. Chapter 1 and 5 are the introduction and conclusion, respectively. Chapter 2 describes the mechanism of temperature oscillation in an LHP. In Chapter 3, a parametric study is conducted using the transient model to understand the necessary condition for temperature oscillation. Chapter 4 describes a new steady-state model of the LHP that can simulate temperature distribution and nucleate boiling in the evaporator core because nucleate boiling in the evaporator core causes temperature hysteresis.

Temperature oscillation occurs when external conditions such as the heat load and sink temperature change. Temperature oscillation is divided into two types: low-frequency, high-amplitude temperature

oscillation, and high-frequency, low-amplitude temperature oscillation. Because these temperature oscillations may cause the temperature of an onboard device of the spacecraft to deviate from the allowable range, the temperature oscillations must be prevented. It has already been found that low-frequency, high-amplitude temperature oscillation occurs when the thermal mass attached to the evaporator is large, the heat load is low, and the sink temperature is lower than ambient temperature. On the other hand, the mechanism of high-frequency, low-amplitude temperature oscillation is not yet fully understood. To date, the mechanism of temperature oscillation has been presented based on the temperature histories of LHPs obtained by experiments. However, no experiments to visualize phenomena inside the LHPs during temperature oscillation have been reported. This means that the mechanism of temperature oscillation has not yet been verified and is still poorly understood. The objective of Chapter 2 is to investigate phenomena during high-frequency, low-amplitude temperature oscillation and to understand the mechanism of the temperature oscillation.

A transient mathematical model of an LHP was developed to understand the mechanism of temperature oscillation. The calculation results showed that temperature oscillation occurs when vapor cannot be completely condensed in the condenser, and a two-phase flow enters the liquid line. The penetration of the two-phase flow into the liquid line is caused by a decrease in the reservoir temperature. The decrease in the reservoir temperature reduces the saturation temperature of the entire LHP and the condensation of the vapor in the condenser becomes more difficult. After the two-phase flow enters the liquid line, the subcooled liquid re-enters the liquid line due to the increase in the reservoir temperature. However, even if the two-phase flow does not re-enter the liquid line, the temperature may continue to oscillate. This is because the condensation length continues to oscillate in the condenser even if the two-phase flow does not re-enter the liquid line. It was also found that when the condensation length oscillates significantly, the temperature amplitude also increases. This means that when the amplitude of the condensation length is small, temperature oscillation does not continue, and the temperatures eventually converge.

In Chapter 3, a parametric study is performed to understand the necessary condition for high-frequency, low-amplitude temperature oscillation and propose a method to prevent the temperature oscillation. To date, conditions for temperature oscillation have been experimentally investigated. These experimental studies have drawbacks such as the difficulty in evaluating the net heat load due to the large heat loss to the ambient. Therefore, numerical analysis is required to understand the condition for temperature oscillation in addition to experimental studies. In recent years, numerical analysis of temperature oscillation has also been performed and instability criteria have been proposed. The instability criteria showed sufficient conditions for temperature oscillation, but the necessary condition has not been understood. However, the necessary condition is required to propose a method to prevent temperature oscillation. A parametric study is performed to understand the necessary condition for temperature oscillation. In addition, a method to prevent temperature oscillation is proposed based on the necessary condition.

First, it was found that a small filling ratio, low thermal conductivity of the wick, high evaporation heat transfer coefficient, and high sink temperature lead to temperature oscillation. These conditions under which temperature oscillations occur are those under which the temperature difference between the reservoir and the condenser is small. As mentioned above, temperature oscillation is caused by the penetration of the two-phase flow into the liquid line. A small temperature difference between the reservoir and the condenser reduces the difference between the saturation temperature and the condenser temperature, and the two-phase flow enters the liquid line. Therefore, the small temperature difference between the reservoir and the condenser causes temperature oscillation. On the contrary, the temperature eventually converges when the heat load is high, even if the temperature difference becomes small, and the two-phase flow enters the liquid line. Therefore, a small temperature difference between the reservoir and the condenser is the necessary condition for temperature oscillation. To prevent temperature oscillation, the temperature difference should be kept high. Heating the reservoir is one of the methods to keep the temperature difference high. Numerical analysis showed that temperature oscillation was preventable by heating the reservoir.

In Chapter 4, a new steady-state model that implements temperature distribution and nucleate boiling in the evaporator core was developed, and the effect of nucleate boiling in the evaporator core was investigated. Nucleate boiling in the evaporator core is considered to be one of the causes of temperature hysteresis. To date, several steady-state models of LHPs have been proposed to predict heat transfer performance. However, only two models have implemented phenomena in the evaporator core. One model can simulate the internal flow and temperature distribution in the evaporator core. The other model implements nucleate boiling in the evaporator core. Therefore, no model implements both temperature distribution and nucleate boiling in the evaporator core. In Chapter 4, a new steady-state model that implements both temperature distribution and nucleate boiling in the evaporator core is developed to quantitatively estimate the effect of the nucleate boiling in the evaporator core on the heat transfer performance of the LHP.

To validate the new model, temperature and heat leak calculated by the new model are compared with experiments in which the evaporator core was visualized with a borescope. The temperatures of the evaporator wall and reservoir obtained from the convective model that does not implement nucleate boiling did not agree with the experimental results, whereas the new model that implements nucleate boiling in the evaporator core was in good agreement with the experiments. When the heat load is lower than 80 W, the experimental and calculated heat leaks are in good agreement. However, when the heat load is higher than 90 W, the experimental heat leak becomes larger than the calculated heat leak. The reason for the difference between the experiments and calculation is that the new model does not implement condensation in the evaporator core.

The influence of nucleate boiling in the evaporator core was quantitatively evaluated using the new model. The calculation results showed that the heat leak with nucleate boiling in the evaporator core is up to eight times larger than the heat leak without nucleate boiling. It was also found that half of the heat load became heat leak when nucleate boiling occurred.

Using the model, a parametric study was conducted to understand the conditions under which nucleate boiling in the evaporator core strongly affects the heat transfer performance of the LHP and the conditions under which nucleate boiling is less likely to occur. When the sink temperature was low, the amount of heat transferred by surface quenching became large. This means that when the sink temperature is low, the LHP is strongly affected by nucleate boiling in the evaporator core. It was found that when the thermal conductivity of the wick is low or when the latent heat of a working fluid is high, that is, the amount of heat conducted through the wick is small, nucleate boiling can be prevented.