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主 論 文 の 要 旨

論文題目　Study on high performance and multi-functionalized loop heat pipe for spacecraft based on understanding of internal heat flow phenomena
（宇宙用ループヒートパイプの内部熱流動現象理解に基づく高性能・多機能化に関する研究）

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論 文 内 容 の 要 旨

This research focuses on the development of high performance and multi-functionalized loop heat pipe (LHP) for spacecraft. LHP with single evaporator and single condenser is a capillary-driven two-phase fluid type heat transfer device, which has already been applied as heat transfer device for electrical components in several space missions. However, LHP is unable to cool multiple separated heat sources. Besides, operating characteristics of LHP will be deteriorated when the radiator was heated by Sun. In order to solve those problems and adjust LHP to operate under the various space thermal environment, the LHP with multiple evaporators and multiple condensers (MLHP) was proposed and studied since the MLHP is able to deal with the various space thermal environment. By now because the operating characteristics of MLHP are complicated and the internal heat flow phenomena are not elucidated, there is no application of MLHP for spacecraft. Therefore the detailed investigation on the understanding of the internal heat flow phenomena of MLHP is necessary. In order to investigate the internal heat flow phenomena of MLHP for spacecraft, in this paper, detailed mathematical models under each thermal environment was established and the visualization experiment was carried out. Based on the knowledge of these works on the mathematical model and the visualization experiment, a MLHP's breadboard model for spacecraft was designed, fabricated and experimentally investigated. The heat transport capability of MLHP under different thermal environments (atmospheric, thermal vacuum) and with different working fluids (acetone, ammonia) was evaluated. Each component's performance, such as the secondary wicks, flow regulators and radiators were evaluated. The internal heat flow phenomena such as the flow regulator effect, the nucleate boiling and the gravity effect in the previous numerical works and experimental works were confirmed in the MLHP's breadboard model. The mathematical model agrees experimental result well.

In chapter1, Development of LHP and MLHP are introduced with the comparison to other heat transfer device for the spacecraft and other two-phase fluid loops. The application of LHP, the visualization study of LHP and the latest research on MLHP's mathematical model and experiment are shown. The current issues of MLHP and the purpose of this research are presented.

In chapter2, since the numerical research of MLHP was insufficient and limited, in this research, corresponding mathematical models under each corresponding condition were established. Compared to the current research, the detailed mathematical models were established to predict each operating mode of MLHP in this study, such as the normal operating mode with both evaporator operating, the heat load sharing mode with single evaporator operating, the surviving mode with single condenser operating. The temperature, pressure and vapor quality at the confluence of vapor line and the confluence of liquid line, the mass flow rate to each flow path under each circumstance were also investigated. To validate the mathematical model, a MLHP with two evaporators and two condensers was fabricated. PTFE wick with 1.2μm pore radius and the acetone were used. Experiment was carried out under the normal operating mode, heat load sharing mode and surviving mode. Heat sinks' temperature was kept at 20/20°C by liquid cooling chilling machine and the evaporators' heat loads were varied from 5W to 45W with the step increment in 5W. The ambience temperature was 25°C. Compared to the experimental result and calculations, the mathematical model predicted the operating temperature of MLHP (compensation chamber's temperature) accurately within 2~3°C temperature difference between calculations and experimental data under each operating mode. Therefore the mathematical models were validated. For the temperature prediction of the whole MLHP, the temperature was predicted well except several places. In normal operating mode the calculations agree experimental data well except that the non-condensable gas (NCG)'s effect resulted in the underestimation of temperature at vapor line. In the heat load sharing mode, the calculations agree experiment data well. Besides the NCG's effect, the nucleate boiling generated in the normal operating mode and heat load sharing mode in high heat loads region caused the underestimation of compensation chamber. In the surviving operating mode, in order to decrease the liquid line confluence's temperature, a capillary structure which is called flow regulator was installed to the upstream direction near the liquid confluence. It is a porous structure which can improve the operating characteristics of MLHP when the vapor cannot be condensed totally in one of the MLHP's condenser because of high temperature by generating capillary force to prevent uncondensed vapor to flow through, thus diverting more working fluid to lower temperature condenser side. In this way, operating temperature is reduced since the low temperature liquid returns to evaporator. In order to evaluate the flow regulator's operating performance, experiment was conducted with flow regulator and without flow regulator, the heat loads were 30/30W and one heat sink was kept 0°C, while another heat sink was kept 0-20-40-60-80°C by liquid cooling chilling machines. The ambience temperature was 25°C. Compared the test result operating with flow regulator and operating without flow regulator, when two heat sinks' temperature was 0/80°C, the evaporators' temperature and the liquid line confluence's temperature in experimental result operating with flow regulator was about 21°C, 32°C lower than the corresponding temperature of MLHP operating without flow regulator, respectively. According to the mathematical model, the ratio of mass flow rate on lower heat sink temperature side to higher sink temperature side was 67:33 under the condition operating without flow regulator and the ratio of mass flow rate on lower heat sink temperature side to higher sink temperature side was 91:9 under the condition operating with flow regulator. In this way, the flow regulator's effect was confirmed through numerical and experimental investigation. When the MLHP operated with flow regulator and the sinks temperature was 0/40°C or 0/80°C, the prediction of liquid line's temperature was lower than the experimental result. The probable reason is that the nucleate boiling occurred at downstream side of higher temperature sink side' flow regulator because of the heat leak through the flow regulator. Future work will focus on more detailed mathematical models to investigate this phenomenon.

In chapter3, since there is no visualization approach on MLHP, a MLHP with two evaporators and one condenser was fabricated to confirm the heat flow phenomenon and vapor-liquid distribution in evaporator core, compensation chamber through transparent glass tube. The condensing flow phenomenon in transparent PFA condensing tube was also observed because few visualization research was conducted on LHP's condenser. Since the gravitational head's effect exists in the ground test, the gravitational head's effect should be investigated at first. In this way, the operating characteristics in spacecraft is able to be predicted by removing the gravity effect. In this MLHP, two evaporators and one condenser were positioned horizontally, with the 36cm positive gravitational head. Compared with the negative gravitational head orientation and horizontal orientation, the positive gravitational head orientation was used because of the multiple operating characteristics, including both the gravity driven region and the capillary-gravity co-driven region. High speed camera was used to observe the condensing flow phenomenon in condenser and the distribution of vapor and liquid in evaporator core, each compensation chamber was recorded by camera with borescope. Two kind of tests were conducted, in the normal operating mode with heating both evaporators, the heat loads were conducted from 10/10W to 110/110W with 10/10W increment in each step. The ambience temperature was 25°C and the heat sink was kept 20°C by liquid cooling chilling machine. According to the test result, gravity effect has caused the less heat leak ratio and longer two-phase flow region in gravity-driven region except the 10/10W, at which heat loads that the gravitational effect resulted in more liquid flowing in vapor line. The capillary force started to drive the MLHP when the heat loads were increased to 40/40W, since the gravitational head became unable to make up the frictional pressure loss of the whole loop. In the capillary-gravitational driven region, the subcooled region was formed in condenser because of the increasing heat leak ratio. The heat leak ratio at 110/110W was 30%, which was too large and need to be reduced in the future. In the capillary-gravity driven region, the flow pattern in condenser was transitioned from semi-annular/wavy flow to slug/bubbly flow to subcooled flow. According to the visualization result in evaporator core and compensation chamber, the bubble generation speed in evaporator was faster in the capillary-gravity co-driven region, which visually confirmed the higher heat leak ratio in capillary-gravity co-driven region. The vapor and liquid distribution is different from the current view, in the current view, vapor only exists in one compensation chamber, while in this research vapor existed in both compensation chambers until the heat loads were increased to 90/90W, where the compensation chamber1 was flooded with liquid. In the heat load sharing mode with heating each evaporator respectively, each evaporator shows the same heat flow phenomenon. When evaporator1 was heated, because of the positive gravitational head, the heat load sharing phenomenon disappeared in the gravity-driven region. The heat load sharing phenomenon generated when the capillary force started to driven the working fluid at 60/0W, the evaporator1 kept operating until the heat loads were increased from 220W to 240W. According to the visualization result, in current view, the operating side's compensation chamber is flooded with liquid because of the subcooled liquid and vapor exists in the unpowered side's compensation chamber at the low heat loads. When the nucleate boiling starts, the vapor-liquid interface exists in the powered side evaporator's compensation chamber because of the increasing heat leak from evaporating surface to evaporator core. Therefore the operating temperature of MLHP switches from unpowered evaporator side's compensation chamber to powered side's compensation chamber. This assumption was also reflected in the chapter2's experimental result. However, in this research, vapor exists in the operating evaporator side's compensation chamber and the unpowered side's compensation chamber was flooded from the beginning because of the higher heat leak from evaporating surface to evaporator core with the combination of SUS primary wick and acetone. When the heat loads were increased to 120/0W, nucleate boiling was observed in the unpowered evaporator core, which caused the unpowered evaporator core's temperature surpassed the powered evaporator core's temperature. In this case, since the vapor-liquid interface existed in the powered evaporator side's compensation chamber and only bubbles existed in the unpowered evaporator core, the powered side's compensation chamber still controlled the operating temperature of MLHP while the unpowered side's compensation chamber was flooded by superheated liquid.

In chapter4, based on the knowledge of mathematical model, flow regulator in chapter2 and based on the knowledge of gravity effect, heat leak in chapter3, an MLHP's breadboard model with two evaporators and two condensers for spacecraft was designed and fabricated to confirm the internal heat flow phenomena occurred in chapter2 and chapter3 and to investigate the heat transport capability of MLHP with different working fluids (acetone, ammonia) and under different thermal environments (atmospheric, thermal vacuum). In this new MLHP, to enhance the thermal transport capability, ammonia and SUS primary wick were employed. Two radiators for heat dissipation in thermal vacuum environment were fabricated and evaluated. Secondary wick was installed between evaporator core and compensation chamber to supply the subcooled liquid to evaporator core directly and decrease the heat leak from evaporating surface to evaporator core by forming the capillary link between evaporator and compensation chamber. Acetone was used as the working fluid at first for demonstration and comparison under atmospheric ambience. The ambience temperature was 25°C and the radiators diffused heat through natural convection. In the normal operating test with heating both evaporators, the MLHP started up at 5/5W and is able to transport 55/55W heat for 1.96m. Temperature oscillation generated at 50/50W and 55/55W, which indicated that nucleate boiling generated in one evaporator core. In the heat load sharing mode with heating each evaporator respectively, the evaporator1 was able to transport 55W, the temperature oscillation occurred at 50/0W and 55/0W. While the evaporator2 was able to transport 115W and no temperature oscillation occurred. The experimental result in heat load sharing mode indicated that the nucleate boiling generated in evaporator core1. The secondary wick's effect was confirmed with the comparison of the heat leak ratio between the MLHP stated in chapter3 and chapter4. According to the experimental result, in the normal operating mode with the total heat loads 100W, the heat leak in chapter4's MLHP was about 40% of the heat leak ratio in chapter3's MLHP. Therefore the secondary wick's effect was confirmed. For experimental result of ammonia under atmospheric ambience, in the normal operating mode with heating both evaporators, the MLHP with ammonia is able to transport 130/130W heat, which was 2.4 times of the MLHP with acetone. Moreover, the operating temperature with ammonia was about 30°C lower than the operating temperature with acetone. Therefore, the higher heat transport capability of MLHP with ammonia was confirmed. In the heat load sharing mode with heating each evaporator respectively, different from the acetone, each evaporator was able to transport 180W heat. That is because the compared to the acetone, the MLHP with ammonia reached temperature limit faster than the nucleate boiling began. After the demonstration of working performance in atmospheric ambience, thermal vacuum test was carried out with thermal environment of -180°C and 10^{-5}Pa. Two flexible heaters were pasted on each radiator to simulate the sun. According to the test result, in the normal operating mode with heating both evaporators, the MLHP was able to transport 130/130W heat for 1.96m, the test was stopped at 130/130W since the adhesive between evaporator and heat block deteriorated at high temperature. The fin efficiency of radiator was estimated as 86.1% from experimental result with the heat loads of 120/120W in normal operating mode. The mathematical models related to different working fluids (ammonia, acetone) and different thermal environments (atmospheric, thermal vacuum) were established. Compared to the experimental result, the calculations appropriate well to the experimental result except at the radiator section because the radiator's temperature was assumed to be uniform. In the surviving mode with the heating condition of 40/40W at evaporators, 0W at one condenser and 0-40-80-100-120-160W at another condenser, the flow regulator's effect was confirmed since the liquid line confluence's temperature was kept close to the flow regulator's temperature on lower temperature condenser side and about 20°C temperature difference between the flow regulator's temperature on higher temperature condenser side.

In chapter5, the conclusion and future's prospect of MLHP were presented.