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国際宇宙ステーション沸騰・二相流実験向け凝縮器の熱流動解析技術に関する研究

～凝縮管における一次元凝縮流動と三次元固体熱伝導の連成解析～

Study of Thermal and Fluid Analysis Technology in Condenser of Microgravity Flow Boiling Experimental Set-up Onboard International Space Station

~Conjugate Heat Transfer Analysis of 1D Condensed Flow and 3D Heat Conduction in a Condensing Tube~

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1. Introduction

Recently, as space development moves toward Moon and Mars exploration missions, it is assumed that spacecraft will become larger and more advanced. As a result, there are concerns about increases in the weight, heat generated, and required heat removal flux of power equipment inside the spacecraft. As problems for thermal control systems, the length of heat transport distances and the required heat removal flux of heat sources increases. It is assumed that future spacecraft development will require a heat removal system with large-scale heat transport to solve these problems. Therefore, it is expected to address these problems by using a boiling two-phase flow loop in the thermal control system of a spacecraft, and in contributing to weight reduction and efficiency improvement of the thermal control system. In order to clarify the characteristics of the boiling two-phase fluid loop in microgravity, an experiment called (TPF = Two-Phase Flow) was conducted on the International Space Station [1]. The condenser exists in this TPF experimental device. Previous studies have shown that the condensation heat transfer coefficient of the condenser decreases in microgravity. However, there are still few examples of condensation heat flow measurements, and there are still many unknowns. So, our final purpose of this study is to quantitatively evaluate the heat transfer characteristics of condensers in microgravity by comparing the TPF experimental results with a thermal mathematical model. In this study, conjugate heat transfer analysis model of one-dimensional condensed flow and three-dimensional heat conduction in a condensing tube was constructed as a basic step of the thermal mathematical model.

2. Two-Phase Flow (TPF) Experiments Overview

2.1. TPF experimental equipment

This study is part of the microgravity experiment "Two-Phase Flow (TPF): Gas-Liquid Interface Formation and Heat Transfer Characteristics Using a Boiling and Two-Phase Fluid Loop" conducted on the International Space Station. **Figure 1** shows an overview of the TPF experimental equipment. In the two-phase flow loop used in the experiment, the test fluid is driven by a pump and the fluid pressure is maintained by an accumulator. The back pressure of the accumulator is open to the cabin, so the system pressure is maintained at about atmospheric pressure. Perfluoro-hexane, the main component of fluorocarbon FC-72, was used as the test liquid. After a pump was driven through the loop, the liquid temperature was raised in a preheater, and two types of heating sections, a copper heating tube and a clear glass heating tube, were placed in parallel to boil the test liquid. The boiling heat transfer coefficient and critical heat flux were measured in the copper heating tube, while the behavior of the boiling flow was observed in the clear glass heating tube. An adiabatic observation section was installed downstream of each heating tube to observe in detail the behavior of the boiling flow in the tube with a high-speed camera. The test liquid then passes through the condenser to be cooled. In the condenser, the pressure drop and condensation heat transfer coefficient during condensation are measured. The condensed test liquid is looped in the same way by a pump.

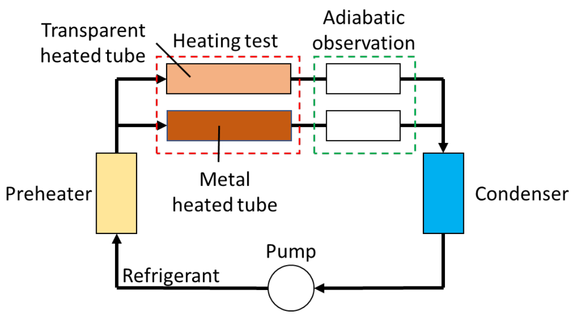
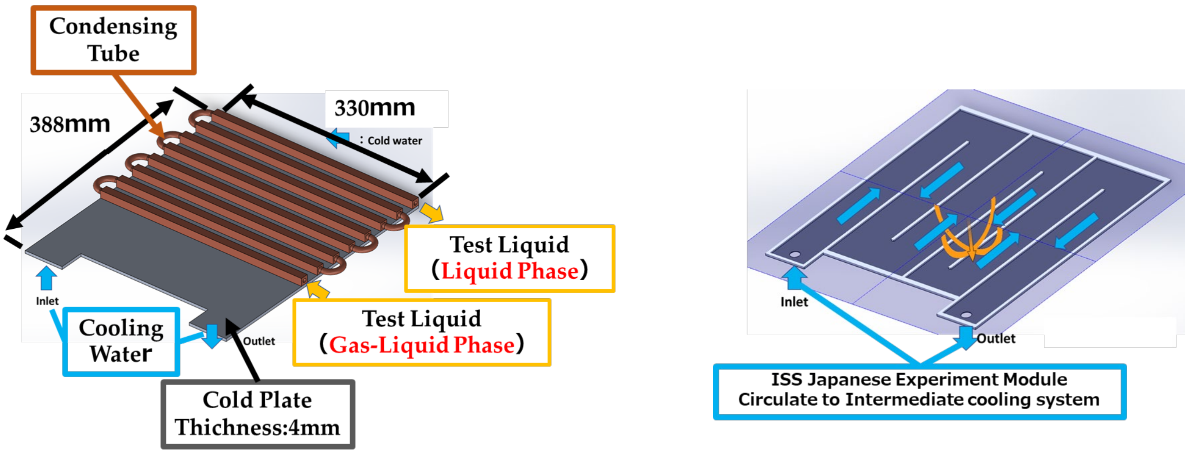


Figure 1. TPF experimental equipment overview.

2.2. Condenser

The condenser in the TPF experimental equipment is mainly composed of condensing tube and cold plate, covered with insulation. **Figure 2** shows (a) an overall view of the condenser and (b) a cross-sectional view of the cold plate. The condenser used in the TPF experiment has a cold plate bonded to the bottom of the condensing tube. The condensing tube, consists of eight rectangular columns with a hollowed-out circular tubes, connected by U-bent tubes. And the cold plate, consists of a flat plate with rectangular channels parallel to it and fins attached to the partition walls between the channels. The test liquid flows in the condensing tube and the cooling water flows in the cold plate. The gas-liquid phase of the test liquid inflows from the condensing tube inlet, condenses to a liquid phase while flowing through the tube, and outflows from the tube outlet. The cold plate, allows the cooling water to be flowed orthogonally to the test liquid through a rectangular flow path in the plate, taking in heat from the condensing tube as it flows and discharging the warmed water from the outlet. The warmed water is cooled by the intermediate cooling system in the Japanese Experiment Module of the International Space Station and the cooled water is sent to the cold plate again. Figure 3 shows a diagram of the heat path between the condensing tube and the cold plate. The gas-liquid phase that flows in from inlet of condensing tube condenses while a liquid film spreads in a circular pattern on the inner wall, and heat is transferred from the liquid film to the tube cross section, thermally conductive adhesive, and cold plate, and finally to the cooling water as waste heat.



(a)Overall view of the condenser. (b)Cross-sectional view of cold plate.

Figure 2. Overview of the condenser.

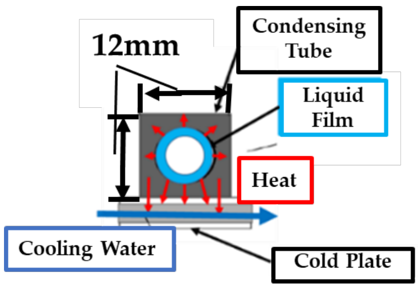


Figure 3. Condensing tube – Cold plate heat path.

3. The conjugate heat transfer analysis

The conjugate heat transfer analysis is constructed one-dimensional condensed flow analysis in a condensing tube and three-dimensional heat conduction analysis of the cross section of condensing tube. Since this is a one-dimensional analysis, the heat transfer in the cross-sectional direction of the tube is uniform. **Figure 4** shows a diagram of the conjugate heat transfer analysis. This analysis is constructed heat transfer between the test liquid and the inner wall of the condensing tube is obtained by one-dimensional condensed flow analysis, heat conduction between the condensing tube cross section, thermally conductive adhesive, and cold plate are obtained three-dimensional heat conduction analysis, and heat transfer between the cold plate and cooling water is obtained three-dimensional flow analysis.

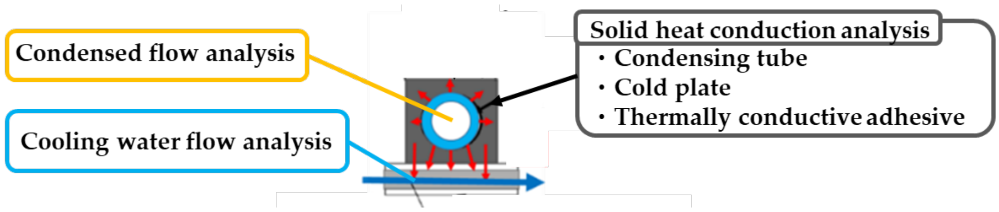


Figure 4. Conjugate heat transfer analysis overview.

3.1. One-dimensional condensed flow analysis

One-dimensional condensed flow analysis used the finite difference. **Figure 5** shows the element split of condensing tube and **Fig. 6** shows the vapor/liquid film control volume diagrams. The analysis method divides the condensing tube in the axial direction from inlet to outlet, sets three assumed values for each divided element, the unknowns of liquid film thickness, interface velocity, and pressure gradient, and solves the governing equations for the conservation laws of mass, momentum, and energy. To determine convergence, the values of interfacial shear stress, interfacial velocity, and pressure gradient derived from the calculation of the basic equations are differed from the assumed values, and convergence is determined when the difference is less than a standard value. If not, the assumed values are changed and the process is repeated until convergence is achieved. By repeating this process from the inlet to the outlet of the condensing tube, the three assumed unknowns can be obtained [2)]. Using the values obtained, the condensation heat transfer coefficient can be calculated and obtained [3)]. **Table 1** shows the analytical conditions used for one-dimensional condensed flow analysis. The inlet pressure and mass flow rate of the boundary conditions at the inlet of the condensing tube were set to match the experimental conditions, and the physical properties of the test liquid were obtained from REFPROP, a refrigerant physical properties database software created by the National Institute of Standards and Technology (NIST) of the United States.

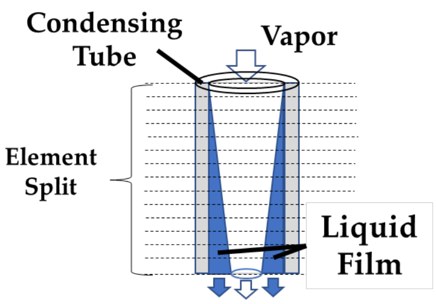
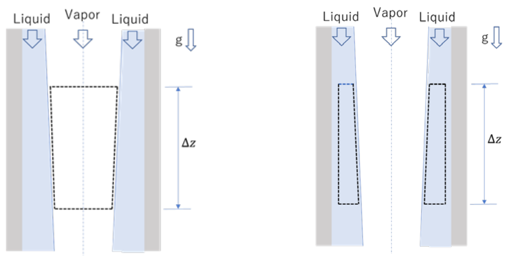


Figure 5. Element split of condensing tube.



(a)Vapor control volume. (b)Liquid film control volume.

Figure 6. Vapor/Liquid film control volume.

Table 1. Analytical conditions used for one-dimensional condensed flow analysis.

Fluid	Inlet Pressure[MPa]	Mass Flux[$kg/s/m^2$]	Saturation Temperature[K]	Latent Heat[kJ/kg]
FC-72	0.11	150	329.68	83.371

3.2. Three-dimensional heat conduction analysis

The final analytical model to be constructed is an analytical model to investigate the heat transfer characteristics of the entire condenser, but this study, as an elemental stage of the analytical model, constructed only for the condensing tube shown in **Fig. 7.** The U-bent tubes are omitted to reduce the analysis load because their influence on the analysis results is negligible. **Table 2** and **Fig. 8** show the correspondence between the boundary conditions of the conjugate heat transfer analysis and the boundary surfaces in the condensing tube. Heat transfer boundary conditions are set for the Inner Wall Surface, which is in contact with the test liquid, the Cold Plate Contact Surface, which is in contact with the cold plate, and the side wall surface, which is in contact with the adiabatic environment. The heat transfer coefficient of the Inner Wall Surface was calculated by one-dimensional condensation flow analysis, and the fluid temperature was set to the latent heat of vaporization under the experimental condition pressure. Heat transfer coefficient of the Cold Plate Contact Surface was set to the average heat transfer coefficient of water, and the fluid temperature was set to the cooling water temperature under the experimental conditions.

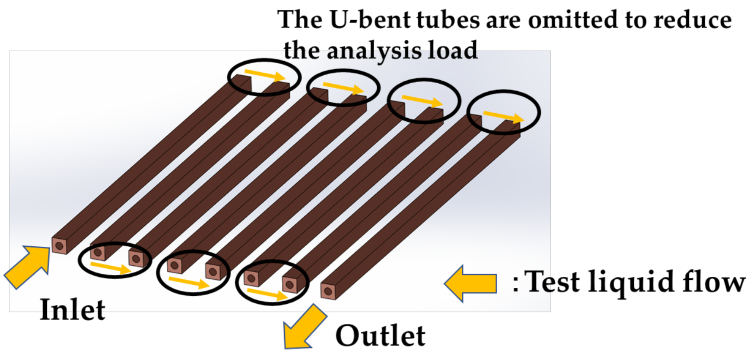


Figure 7. Condensing tube used for conjugate heat transfer analysis.

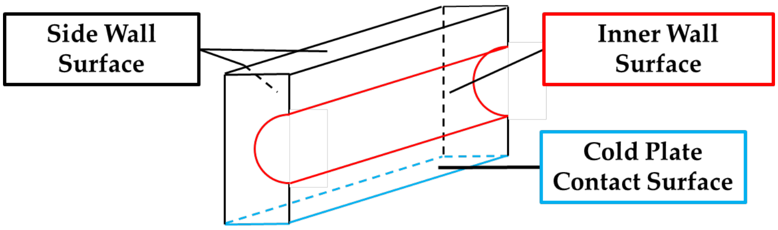


Figure 8. Corresponding surface of condensing tube boundary conditions.

Table 2. Boundary conditions of three-dimensional heat conduction analysis.

	Heat Transfer Coefficient[$W/(m^2 * K)$]	Fluid Temperature[K]
Inner Wall Surface	One-dimensional Condensed Flow Analysis	330.15
Cold Plate Contact Surface	3500	291.15

4. Result

4.1. Result of one-dimensional condensed flow analysis

The results of the one-dimensional condensed flow analysis are shown in **Fig. 9**, **Fig. 10**, and **Fig. 11. Figure 9** shows the axial non-dimensional distance, which is the total length of the condensing tube divided by the inside diameter, and the liquid film thickness, **Fig. 10** shows the axial non-dimensional distance and the absolute pressure, and **Fig. 11** shows the axial non-dimensional distance and the condensation heat transfer coefficient. **Figure 9** shows that the axial dimensionless distance increases sharply from around 400. This is thought to be due to the fact that the test liquid condensed near the condensing tube outlet cannot spread sufficiently in the circumferential direction of the condensing tube due to the liquid film already existing in the tube, but spreads in the radial direction (liquid film thickness direction) resulting in a rapid increase in the liquid film thickness of the test liquid. **Figure 10** shows that the absolute pressure value became constant toward the outlet of the condensing tube, and the pressure gradient decreased. **Figure 11** shows that the condensation heat transfer coefficient is the largest in the area where a thin liquid film is formed between the inner wall and the test liquid near the condensing tube inlet, and that the condensation heat transfer coefficient decreases as the axial distance increases. The tendency of this graph agrees with the tendency of related papers [2]. We will evaluate the accuracy of the model by comparing the results of one-dimensional condensed flow analysis such as the condensation heat transfer coefficient and the pressure gradient with the results of TPF experiments.

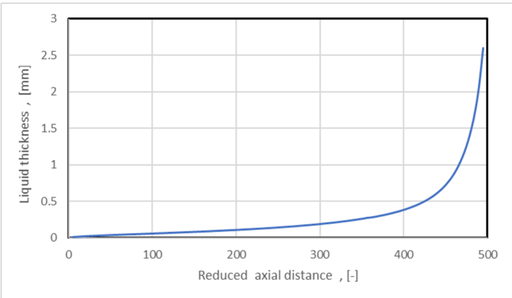


Figure 9. Liquid film thickness distribution.

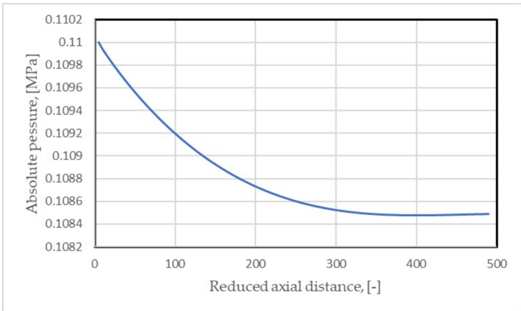


Figure 10. Absolute pressure distribution.

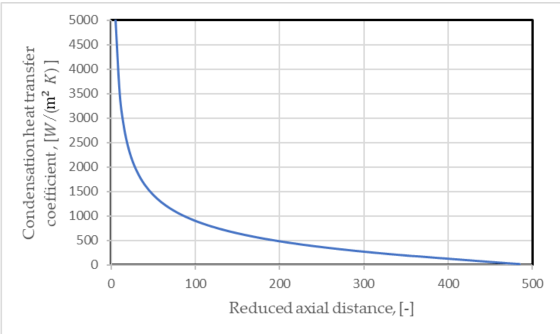


Figure 11. Condensation heat transfer coefficient distribution.

4.2. Result of three-dimensional heat conduction analysis

As a result of the analysis, the temperature distribution of the condensation tube as shown in **Fig. 12** was obtained. **Figure 13** shows the change in the cross-sectional temperature distribution from the condensing tube inlet cross section to the outlet cross section of the three-dimensional heat conduction analysis. The upper temperature in the figure indicates the maximum temperature of the cross-section within the segmented section, and the lower temperature indicates the minimum temperature of the cross-section. The temperature distribution in the cross section shows that the difference between the high and low temperature points decreases from the condensing tube inlet to outlet. This trend can be considered that the condensation heat transfer coefficient obtained by the one-dimensional condensed flow analysis decreases toward the downstream of the condensing tube, the amount of heat passing from the inside of the tube to the cold plate contact surface is reduced, and a decrease in the temperature difference within the solid wall. The results of this analysis show that the results of the one-dimensional condensed flow analysis are reflected in the results of the three-dimensional heat conduction analysis. It can be considered that a rational solution was obtained from this result.

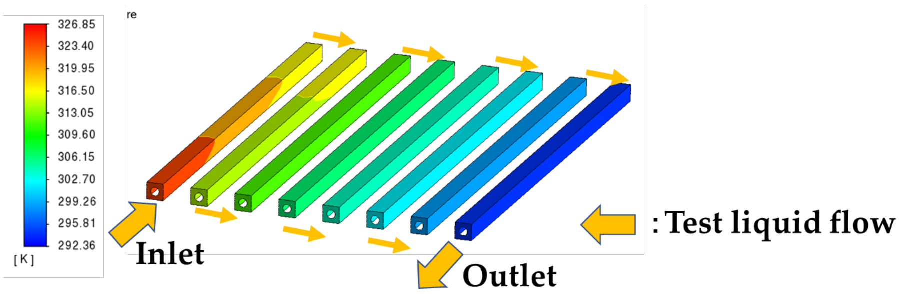
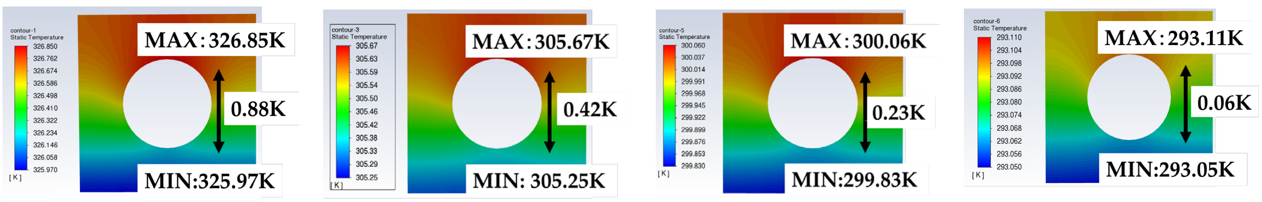


Figure 12. Condensing tube temperature distribution.



Z=0m Z=1m Z=2m Z=2.5m

Figure 13. Temperature distribution in each cross section. (Z is the distance from the inlet).

5. Conclusion

As a result of our study, we were able to construct a one-dimensional condensed flow analysis tool for a test liquid in a condensing tube and conduct a conjugate heat transfer analysis of one-dimensional condensed flow and three-dimensional heat conduction in a condensing tube only, which is an elemental step in the construction of a conjugate heat transfer analysis of a condenser in TPF experiments. Future plans include conducting an analysis that reproduces the flow inside the cold plate, constructing a conjugate heat transfer analysis of the cold plate and condensing tube, and improving the accuracy of the analysis model by comparing the results of the analysis with those of the TPF experiment.

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