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二相流体ループシステムの必要性とメリット 実現への課題

Necessity, Advantage and Challenge for Practical Realization of Two-Phase Flow Loop System

松本聡 [1]
Satoshi MATSUMOTO[1]
1　宇宙航空研究開発機構，Japan Aerospace Exploration Agency

1. Introduction

Future space activity would be expanded to much more advanced missions and an exploration of deeper outer space. For example, a human exploration strategy is being discussed among the international space agencies in the International Space Exploration Coordination Group (ISECG). The ISECG released the global exploration roadmap in 2018 [1)]. As for artificial satellites, commercial communication satellites are being enlarged, and 25 kW class power consumption equipment is planned along with higher functionality and higher performance of communication equipment to support large-capacity communication. The space systems must become larger and higher performance. In this situation, the excess heat should be removed appropriately for always the best performance and long life. Power consumption may increase by several orders of magnitude in the future (order of several tens of MW). And the heat density of high-performance electric devices such as power semiconductors would reach several MW/m^2. In order to support the upcoming space activities, a thermal management is one of key technologies. Currently, heat pipes and a pumped single phase cooling system are used in the artificial satellites, the exploration rovers, and even in the International Space Station. The coverage map of each thermal management system on the amount of removable heat transfer and heat flux is shown in **Fig. 1**. The trade-offs regarding the strengths and weaknesses of applying each thermal control system to spacecraft is summarized in **Table 1**. The requirement of a thermal management system for next generation is three major issues: (1) large amount and long distance of exhaust heat, (2) high heat density, (3) uniform temperature among heat sources. Two-phase pumped loop system is very promising to meet these demands [2)].

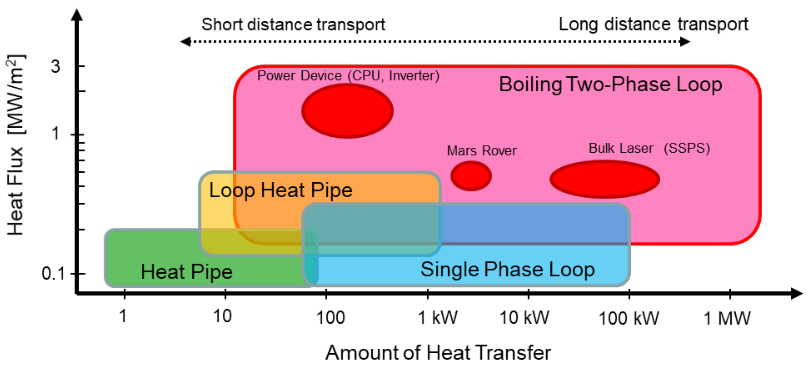

Fig. 1　Schematic map of coverage of thermal management system on amount of heat transfer versus heat flux

Table 1 Trade-off of thermal management systems for space application

Type	Amount of Heat Transport	Processabl eHeat Flux MW/m^2	Distance of Heat Transport	Mass/Size	Electric Power	Practical Use for Ground	Practical Use for Space	R&D for Space Application	Note
Heat Pipe (HP) [Latent heat, Two-phase]	×	×	×	●	●	●	●	●	
	< 100W	~0.2	order of 10 cm	Mini	Unnecessary	Various heat generating equipment	Various artificial satellite	Improved as a practical technology	Easy heat transport Widely used for practical use Light, thin, short and small
Loop Heat Pipe (LHP) [Latent heat, Two-phase]	▲	▲	×	●	●	▲	●	▲	
	10W～1kW	~0.5	10 cm ～Several m	Mini	Unnecessary	Smart Cell Phone, Power Electronics	MAXI (40W), SWIFT	Technology acquisition through space demonstration	High performance heat pipe Light, thin, short and small
Single-Phase Pumped Loop [Sensible heat]	●	▲	●	×	×	●	●	●	
	< Several 10kW	~0.3	~ Several 100 m	Heavy/Large	Necessary	Various large-capacity heat generating devices (Engine, CPU)	ISS, Space Shuttle	Improved as a practical technology	Existing large-capacity exhaust heat Profound and long Large-capacity exhaust heat requires a large amount of power and is inefficient
Boiling Two-Phase Pumped Loop [Latent heat, Two-phase]	●	●	●	▲	▲	●	▲	×	
	100W ~ several 10 MW	~3	~ Several 100 m	Heavy/ Large	Necessary	Supercomputer (1 MW), Railway substation (6000 MW), Thermal power / nuclear power plant	AMS	Acquisition of basic characteristics in zero gravity Building a design database	As a next-generation heat transport device, it has the advantages of large capacity, high heat generation density, and long-distance transport.

● : advantage
▲ : moderate
X : disadvantage

This paper describes the features of two-phase flow pump loop system and issues to be solved when it applies to future space activity for the thermal management system.

2. Two-phase Pumped Loop System

In a large platform in space such as the International Space Station, the single-phase loop cooling system is employed for a thermal management. The pump pushes the coolant to the heat generation part of payload section, where it carries away the heat in a cold plate. The heat is absorbed as sensible heat and rises the temperature of coolant. Typical temperature increase is 20 to 30 K. Then, the boiling point of the coolant is never exceeded. The heat removal capacity is determined by the specific heat of the coolant, the mass flow rate, and the temperature difference.

The conceptual diagram of the two-phase pumped loop cooling system is shown in **Fig. 2**. A pump is also used to circulate a coolant and accumulator is equipped to absorb the volume change and saturation temperature of the coolant. The heat produced in the electrical devices is removed in the evaporator where the coolant vaporized. The heat removal is more efficient than the single-phase loop. The heat removal capacity is governed by specific latent heat of vaporization, the vapor mass fraction and mass flow rate. The heat removal efficiency by latent heat is much higher than that by sensible heat, and if the system has the same heat removal performance, the mass flow rate by the pump may be small. Further, even if the amount of heat exhausted from the heat generating device changes, the temperature on the heat transfer surface of the evaporator is maintained at the saturation temperature, and the temperature uniformity is excellent. In the case of the radiator as condenser, the fluid temperature kept high around the saturation temperature, which means the thermal radiation efficiency of the radiator will improve, and the radiator area can be reduced.

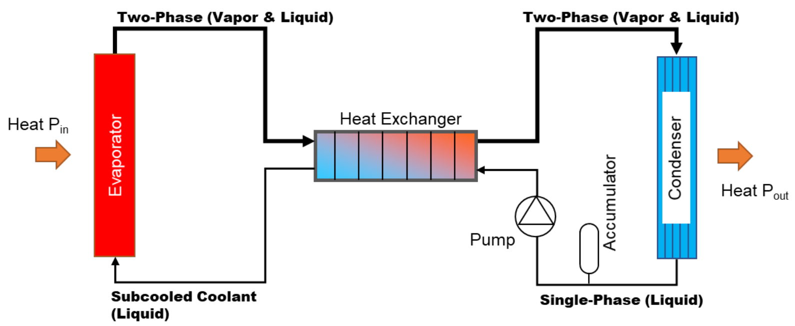

Fig. 2 Conceptual diagram of thermal control system with two-phase pumped loop

There are two main issues when applying the loop to space. The heat transfer coefficient at heat transfer surface is not clear under microgravity conditions. Boiling two-phase fluid loops have greater heat removal capacity than single-phase fluid loops, but on the other hand there are some things to be aware of. The heat flux at the heat transfer surface is getting enlarger, void fraction might be large, and ultimately dry-out occurs at the surface. This situation is very critical because the surface temperature rises rapidly, and the evaporator burns out at the critical heat flux.

In order to design a thermal control system for a space application, it is necessary to understand the gravity dependence of heat transfer and critical heat flux. The group of Ohta and Asano et al. conducted microgravity experiments on the ISS to clarify the boiling and condensation heat transfer affected by the gravity [3-5].

3. Concluding remarks

The outline, advantages, and issues of boiling two-phase pumped loop system for thermal management were described in comparison with heat pipes and single-phase loops. The boiling two-phase loop has excellent heat removal capability that is expected to be applied to large spacecraft, but in order to put it into practical use, it is necessary to accurately grasp the gravity dependence of the boiling heat transfer, the condensation heat transfer, and the critical heat flux. Therefore, the results of space experiments conducted by Japanese group on the ISS/Kibo will provide very important knowledge for not only for the progress of heat transfer science and engineering but also for promoting practical application.

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