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P25

円管内における強制流動沸騰熱伝達の過渡特性

Transient Characteristics of Forced Flow Boiling Heat Transfer in a Circular Tube

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1. Introduction

Space has special features not found on Earth, such as microgravity, high vacuum, and vastness, and activities that take advantage of these features are becoming increasingly popular. On the other hand, heat transfer equipment cannot be easily maintained or replaced in the event of a malfunction. In addition, rocket launches are expensive and require designs that minimize waste to the greatest extent possible. Specifically, the equipment must be lightweight, consume less power, and deliver reliable heat transfer performance in space.

The current problem lies with the growing heat load that needs to be appropriately managed in space. This is due to an increase in the amount of exhaust heat as spacecrafts and satellites become larger, and an increase in heat generation density as electronic equipment becomes smaller. Therefore, a very efficient and high capacity heat removal system is required. Two-phase heat transfer schemes such as boiling attracts increasing attention. Boiling has a number of advantages over conventional heat removal schemes employing single-phase heat transfer. For example, flow boiling utilizes latent heat, which enables cooling at a smaller flow rate than conventional systems and reduces the overall weight of the system, and it has a high heat transport capacity and extremely good temperature controllability. Microgravity experiments of flow boiling heat transfer onboard the International Space Station (ISS) were performed with a wide variety of parameter such as mass flow rate, heat flux, and two types of heat transfer tube[1)].

However, many issues remain in the practical application of cooling systems using flow boiling under microgravity conditions, such as understanding the gravity dependence, modeling the heat transfer characteristics, and improving the cooling performance. Among them, the improvement of cooling performance entails reducing cooling surface temperature in ground experiments, raising the heat transfer coefficient of the industry vessel, and improving-critical heat flux (CHF).

Therefore, the objective of this study is to understand the transient characteristics of flow boiling under fluctuating heat loads in order to design a two-phase boiling cooling system. In this paper, the heat transfer characteristics of flow boiling, especially the transient temperature variations occurring in a metal heat transfer tube, were investigated.

2. Experimental setups

A schematic diagram of the system used in this study is shown in **Figure 1**. The system consists of five major components: a pump, a preheater, the test section, a condenser, and an accumulator. Perfluorohexane was used as the test fluid, which was circulated through the closed system. The liquid was evaporated in the test section to absorb heat, cooled in the condenser to condensate vapor to liquid, and it was circulated by the pump. In this circulation, the accumulator was responsible for compensating for the volume expansion when boiling occurred. The possibility of heat overload is considered in the event of a sudden increase in exhaust heat or a sudden rise in the refrigerant temperature.

In this study, a metal heat transfer tube with an inner diameter of 4 mm was used in the test section for the heat transfer measurements. This metal tube is shown in **Figure 2**. The tube was equipped with 10 thermocouples at an interval of 33.5 mm, which were numbered #1 to #10 from the inlet to the outlet of the tube. A heat load was applied to the metal tube, and the transient characteristics up to CHF were investigated for each thermocouple. The measurement was performed under a mass flow rate of 200 kg/(m^2s) and a subcooling degree of 10 K.

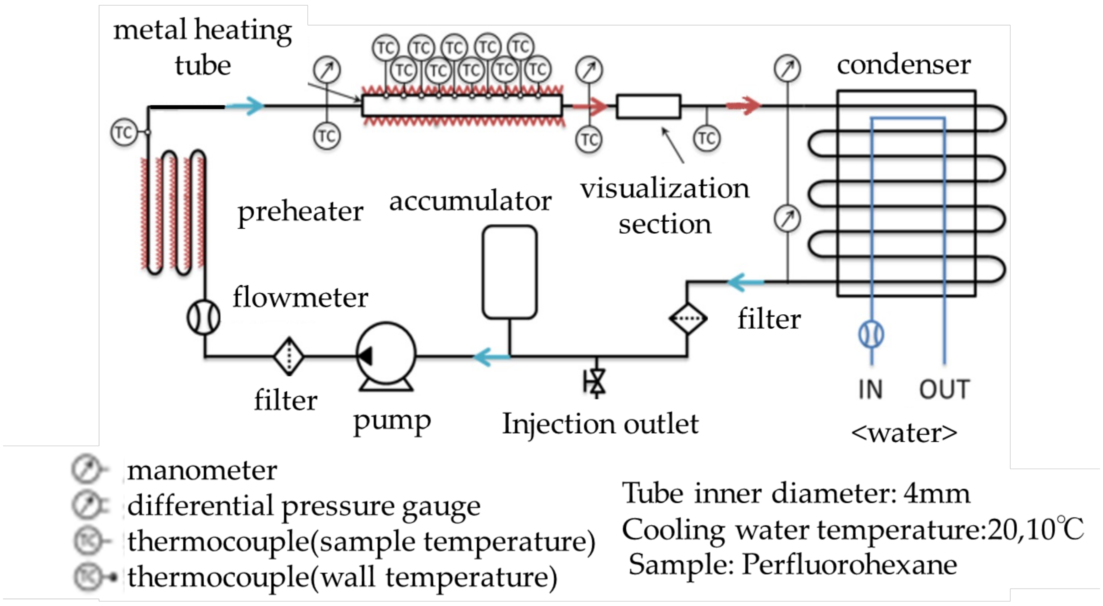


Figure 1. Schematic of the experimental apparatus.

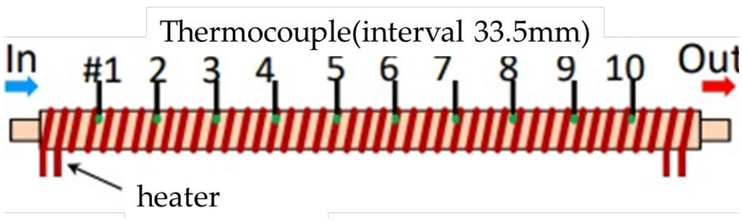
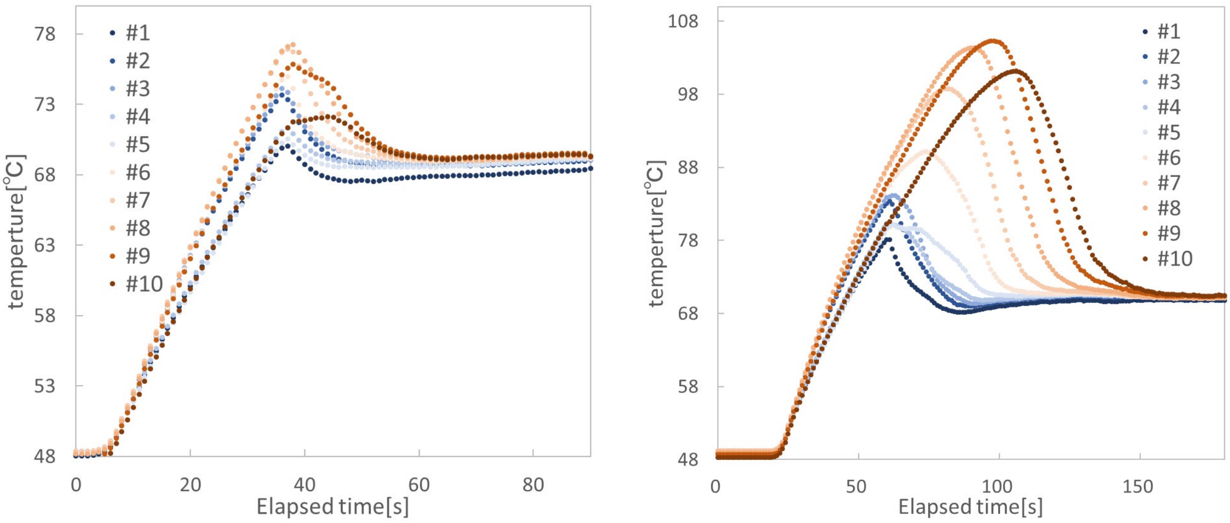


Figure 2. Schematic of the metal heating tube.

3. Results and discussions

3.1. Influence of the inflow temperature of the test section

When boiling occurs in a metal heat transfer tube, a rapid drop in temperature can be observed in the readings of the thermocouples (#1~#10) of the metal heat transfer tube. This abrupt change is due to the elevated heat removal from the heated wall induced by the transition from single-phase convection to boiling. It was predicted that the stability of the temperature of the liquid flowing into the test section would affect the timing of boiling at each point. In other words, under varying inflow temperatures, boiling tends to occur with a staggered time delay. In **Figure 3**(a), boiling occurred at all locations almost simultaneously within 10 seconds of each other, whereas there was a significant time delay in 3(b), about 45 seconds between #1 and #10.



(a)Simultaneous onset of boilong (b) Staggered onset of boiling

Figure 3. Effect of the inflow temperature

3.2. Dryout

Excessive heat load is expected to cause dryout in the metal heat transfer tube due to a lack of liquid on the heated surface. In particular, the area near the tube outlet (#10) is most likely to dry out in this experiment. When a moderate heat load is applied, the thermocouple at the center of the tube shows the highest temperature because heat escapes near the exit of the metal tube in the direction of the flow through the tube. However, when excessive heat load is applied, the temperature near the exit side of the metal tube tends to be the highest.

The temperature changes before and after reaching dryout are shown in **Figure 4**. A total heat load of 80 V and 2.2 A was applied to the metal heat transfer tube, and the voltage was increased by 1 V per line. Initially, #4 had the highest temperature reading. The thermocouple near the outlet shows a rise and fall in temperature. Then, after applying a voltage of 83V for 360 seconds, thermocouples #10~7 show a higher temperature than #4. Therefore, this change is considered to be the beginning of dryout.

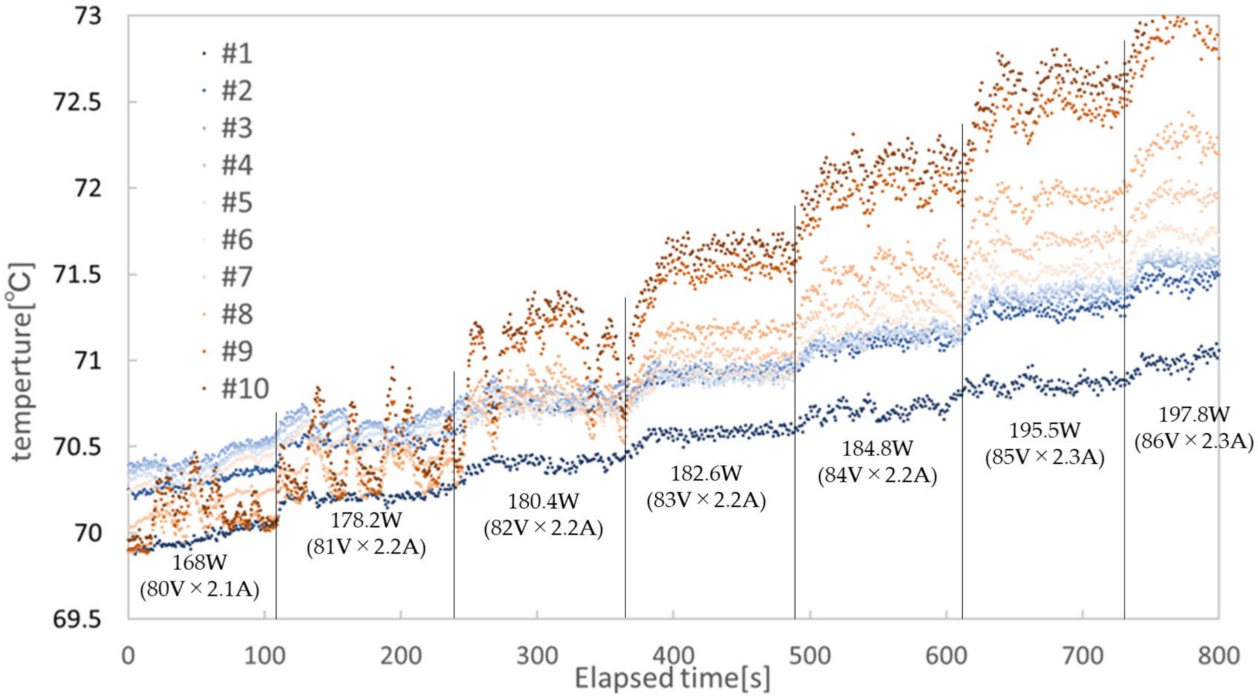


Figure 4. Time variation of temperature measured vicinity of heated surface Transient temperature variations under a stepwise increase of heat load.

3.3. Critical Heat Flux

Once dryout occurs, CHF is expected to be reached by further applying increasing heat load. The rate of temperature rise at the locations where CHF has been reached is significantly larger than where CHF is yet to occur.

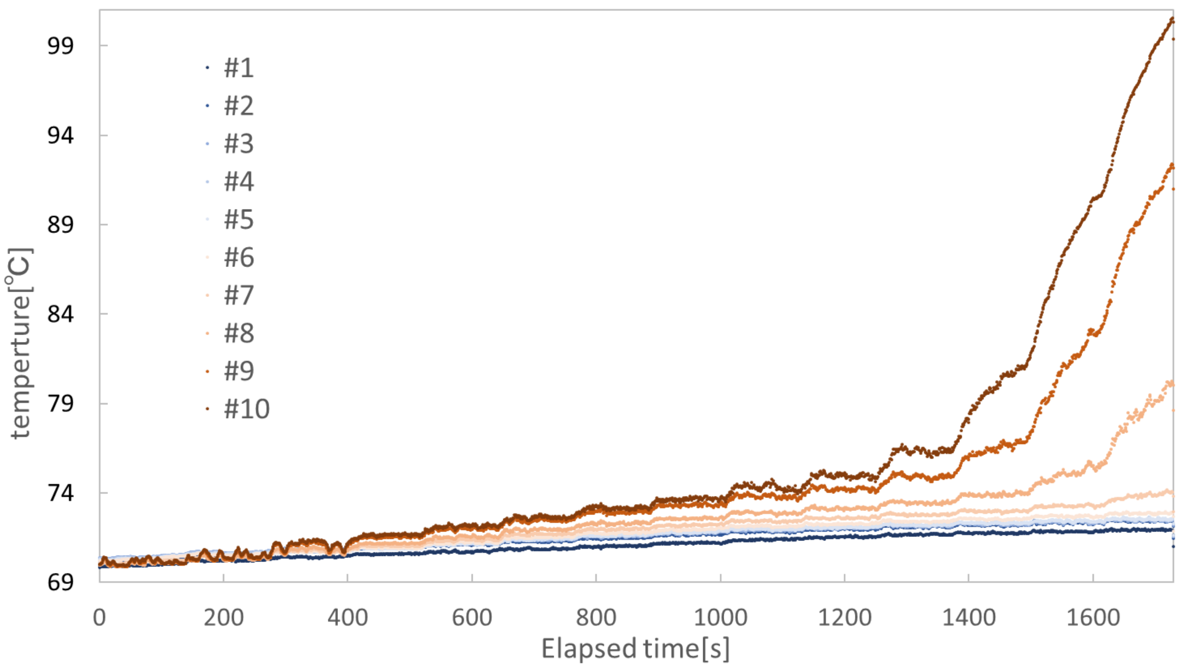


Figure 5. Long-term temperature variations.

Increasing voltage continued to be applied to the metal heat transfer tube and the post-boiling conditions are shown in **Figure 5**. It can be seen that the rate of temperature rise at #10 becomes lager rapidly after an elapsed time of around 1400 seconds. From this point on, it can be considered that CHF is reached at this point.

4. Conclusions

We were able to confirm the dryout in forced flow boiling inside a metal heat transfer tube and the transient characteristics up to CHF.

(1) It was suggested that the timing of boiling at each location along the inner tube may differ depending on the stability of the inflow temperature.

(2) The behavior and the threshold heat load of dryout were confirmed.

(3) The heat load under which CHF occurred and the temperature variations before and after CHF were confirmed.

References

1) Inoue, K., Ohta, H., Toyoshima, Y., Asano, H., Kawanami, O., Imai, R., Suzuki, K., Shinmoto, Y., Matsumoto, S.: Heat loss analysis of flow boiling experiments onboard International Space Station with unclear thermal environmental conditions (1st Report: Subcooled liquid flow conditions at test section inlet), Microgravity Sci. Technol. (2021)