Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2023

Experimental Investigation of Impact of Sodium Heat Pipe Geyser Boiling on Microreactor System

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Keywords : Sodium heat pipe, Geyser Boiling, Temperature Oscillation, Thermal Performance

1. Introduction

The heat pipes are advanced heat transfer devices that offer effective heat transfer compared to traditional heat transfer methods. They transfer the heat by utilizing two-phase heat transfer with minimal temperature differences between the heat source and the heat sink. Furthermore, the heat pipe does not require electricity in terms of operation. Therefore, interest in heat pipes is increasing in the nuclear industry. Starting with space nuclear reactors, the utilization of heat pipes as passive systems and the proposal of heat pipe-cooled reactors have been suggested. In particular, the nuclear field has started utilizing liquid metals as a working fluid in high-temperature systems due to their high-temperature conditions. Hence, the investigation of liquid metal heat pipes has been actively conducted.

Among various phenomena of heat pipes, extensive research has been conducted on Geyser boiling, excluding steady-state operation [1-2]. Geyser boiling was observed only in thermosiphons without a wick structure. However, it has also been discovered in liquid metal heat pipes when they are operated vertically. In the current proposals for heat pipe-cooled microreactors, horizontal orientations are commonly suggested. In the case of microreactors, they can be utilized in mobile applications and remote locations with limited human presence. Considering the potential scenarios of transportation accidents, earthquakes, and various other accident situations, it becomes crucial to investigate the heat transfer performance under the vertical conditions of the heat pipe. Geyser boiling is characterized by the sudden release of vapor bubbles in large quantities, leading to a temporary increase in the heat pipe's internal pressure. Under certain circumstances, the vapor bubbles accumulate near the heated end of the heat pipe instead of being carried smoothly to the condenser. When a critical mass of vapor bubbles gathers, it can lead to a sudden surge or an explosive release of vapor. This sudden vapor expulsion is what characterizes Geyser boiling. The process of Geyser boiling is shown in Fig. 1. The significance of Geyser boiling lies in its association with abrupt temperature changes. Temperature oscillation could influence the operation of nuclear reactors, such as heat removal performance, and doppler effect.

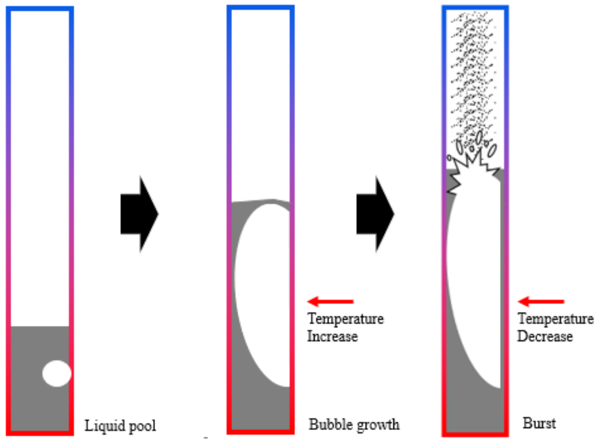

Fig. 1. Progress of Geyser boiling.

Until now, investigations of the Geyser boiling phenomenon in heat pipes have primarily focused on monitoring the temperature changes of the heat pipe itself. However, in nuclear power plants, the most crucial aspect is understanding how Geyser boiling can affect the temperature of nuclear fuel, potentially leading to the Doppler effect, and whether it can reliably remove heat. Therefore, this study experimentally investigates the impact of Geyser boiling on cladding temperature and assesses its effectiveness in heat removal to ensure nuclear safety and stability. This study would be highly important to ensure the safety and efficiency of the heat pipe-cooled microreactors in diverse operational conditions.

2. Modeling and Methodology

In this section, the conditions used to evaluate the impact of Geyser boiling are described. The description includes configuration of heat pipe and experimental facility.

2.1 Liquid metal heat pipe

Sodium with a purity of 99.7% was employed as the working fluid. The total length of the heat pipe was 900 mm, utilizing stainless steel 316 as the material, which is a commonly proposed material for Microreactors. The outer diameter was 19.05 mm (3/4 in) with a thickness of 1.24 mm. 120# screen mesh wick, with a thickness of 1.12 mm, was utilized. Geyser boiling phenomena is typically extreme under high filling ratio and low power conditions. Therefore, the filling ratio was set at 59.2 g, corresponding to 260% of the wick volume. The investigation of the liquid metal heat pipe was conducted with an evaporation section of 200 mm, an adiabatic section of 300 mm, and a condenser section of 400 mm. These are summarized in Table 1.

Table I: Liquid metal Heat Pipe Description

Parameters	**Liquid metal heat pipe**
Length	900 mm
Diameter	19.05 mm
Thickness	1.24 mm
Length of evaporation	200 mm (22.2%)
Length of adiabatic	300 mm (33.3%)
Length of condenser	400 mm (44.4%)
Wick thickness	1.12 mm (120#)
Filing ratio	260% (59.2 g)

2.2 Experimental facility

The microreactor proposed by Los Alamos National Laboratory (LANL) has been considered a reference among the various heat pipe cooled microreactor designs [3]. In LANL's microreactor, the monolith core is made of Stainless Steel 316. The diameter of the holes for the fuel is 14.25 mm, and the distance between the heat pipe and the fuel is suggested to be 1 mm. Based on the analysis results of LANL's heat pipe cooled microreactor, adjustments in thermocouple (TC) locations were made, considering the temperature differences between fuel-to-fuel and fuel-to-heat pipe interfaces. To ensure proper TC locations, the distance between the fuel and heat pipe was set to 5 mm (3 mm, except TC). The gap between the stainless steel block and the heat was 0.1 mm. Therefore, the cartridge heater diameter was 14 mm, and the block was made of stainless steel 316.

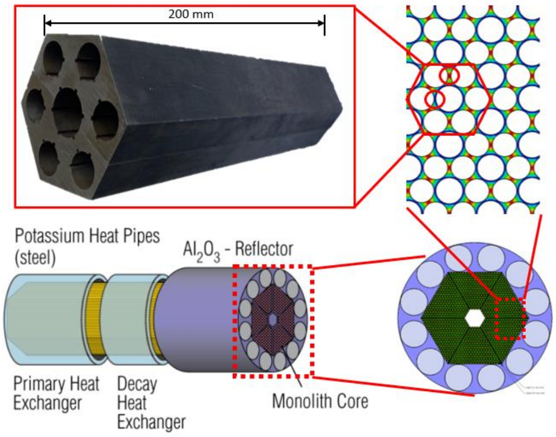

Fig. 2. Flowchart of stainless steel 316 block manufacture. [4]

The experimental facility is composed of the test section, the air jacket for the condenser section, the stainless steel 316 block with 6 cartridge heaters for the evaporation section, the nitrogen tank, and the pump that adjusts the nitrogen flow for the condenser section. The schematic of the test facility is shown in Fig. 3 (a). The cooling condition of nitrogen gas was 230 lpm and 19 ℃ inlet temperature. Heat removal rate was calculated by eq (1).

$$Q_c = \dot{m} c_p (T_{out} - T_{in}) \qquad (1)$$

The heating conditions were varied from 500 W to 1000 W at 90° degree. The temperature distribution was acquired from K-type TCs installed on the cartridge heater, evaporator, adiabatic, condenser sections, inlet, and outlet of the condenser. The schematics of the heat pipes are represented in Fig. 3(b) with TCs location. TCs are installed on the surface of the heat pipe.

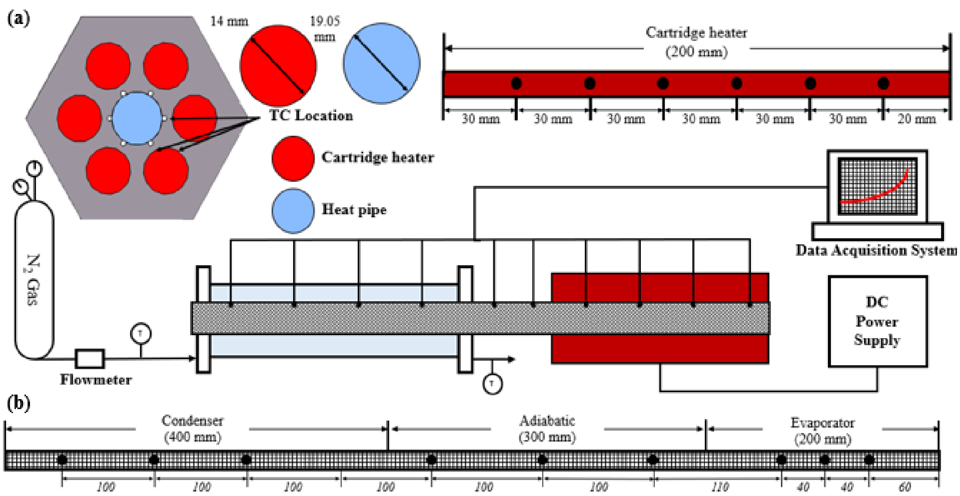

Fig. 3. (a) Configuration of experiment facility, (b) location of TCs in heat pipe.

Table II: Summary of temperature and heat removal rate oscillations

Power [W]	Period [s]	Amplitude (Average)				
		Heater – Heater [K]	Heater – Heat pipe [K]	Evaporator [K]	Condenser [K]	Heat removal rate [W]
500	91	3.238 (0.5%)	**4.100 (0.6%)**	**34.81 (5.44%)**	**27.35 (15.1%)**	7.71 (2.54%)
600	52	2.136 (0.3%)	**2.830 (0.4%)**	**32.20 (4.90%)**	**38.45 (17.3%)**	5.91 (1.45%)

Power [W]	Amplitude (Maximum)			
	Heater – Heater	Heater – Heat pipe	Evaporator	Condenser
500 (Decrease)	**7.059 (1.0%)**	6.612 (1.0%)	**55.24 (8.59%)**	**69.50 (45.7%)**
600 (Decrease)	**5.089 (0.7%)**	4.193 (0.57%)	**53.21 (8.12%)**	**108.2 (42.5%)**

3. Results and Discussions

The influence of Geyser boiling showed significant variations under low-power conditions, Including oscillation of the heater temperature and heat removal performance. Therefore, based on the results obtained under low-heat conditions, the investigation was conducted to assess the impact of Geyser boiling on the heater and heat removal performance. Average temperature oscillation information and the maximum temperature oscillation are summarized in Table 2. For the impact investigation of Geyser boiling, data from the steady-state oscillation were utilized.

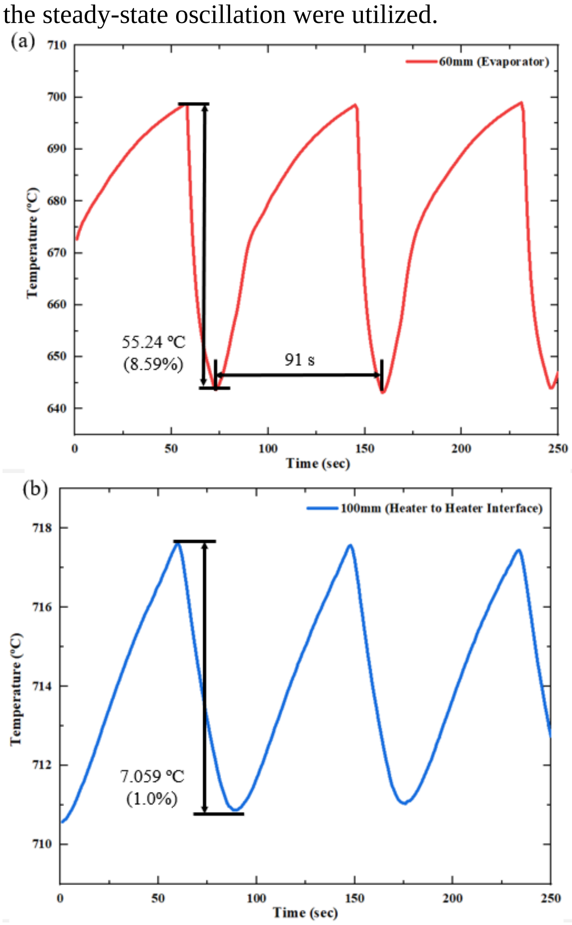

Fig. 4. (a)Temperature Oscillation in evaporator section and (b) heater to heater interface due to the Geyser boiling [Maximum, 500 W].

3.1 Impact of Geyser boiling to heater

The average temperature amplitude and period presented in Table 2 represent the mean of all temperature fluctuations in each section. From an overall perspective, it can be observed that the heater's surface temperature fluctuates by approximately 0.5% during the roughly 5% oscillation in the Evaporation section. From a maximum amplitude viewpoint, the heater's surface temperature fluctuates by approximately 1% during the approximately 9% oscillation in the Evaporation section. Considering a measurement error of 0.75% for the K-type TC, the influence of the Geyser boiling to the heater is negligible. The behaviors of the maximum amplitude for the heater and the evaporation section of the heat pipe are illustrated in Fig. 4.

3.2 Impact of Geyser boiling to heat removal performance

The average temperature oscillation in the condenser section had a more significant impact compared to the evaporation section. As a result, its influence on heat removal performance was larger. At 600W, the amplitude exceeded 100 ºC, but the impact on heat removal performance was approximately 6W. While Geyser boiling had the most significant effect on heat removal performance at 500W, the difference was only about 8W. Even in the most influential region, the impact was approximately 3%. This is represented in Fig. 5.

Therefore, for periodic Geyser boiling, the impact on nuclear fuel temperature and heat removal performance is considered relatively insignificant. However, as shown in Fig. 6, in cases where Geyser boiling occurs without a periodic pattern, the influence on nuclear fuel could not be ignored. In such scenarios, the impact is significant, and further investigation is necessary. Therefore, additional research on such phenomena should be conducted to better understand and address their effects on the system.

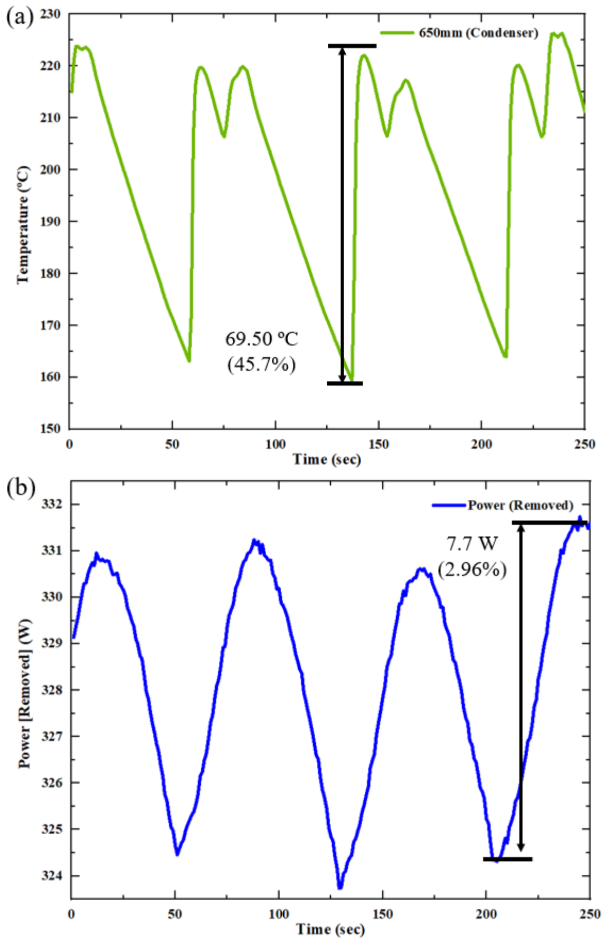

Fig. 5. (a) Temperature Oscillation in condenser section and (b) removed power oscillation due to the Geyser boiling [Maximum, 500 W].

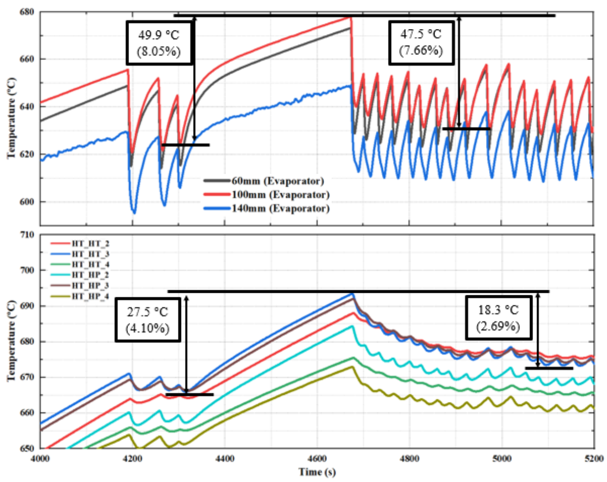

Fig. 6. Impact of geyser boiling in transient condition (a) Evaporator section of heat pipe (60 mm, 100 mm, 140 mm) and (b) heater to heat pipe and heater to heater interface (60 mm, 100 mm, 140 mm).

3. Conclusions

This study investigated the impact of Geyser boiling on a heat pipe-cooled microreactor's performance, particularly its influence on nuclear fuel temperature and heat removal efficiency. The findings revealed that periodic Geyser boiling had minimal effects on the microreactor's performance, as the heater's surface temperature showed insignificant fluctuations during oscillation. Even at maximum amplitude, the impact on the heater was negligible, considering the thermocouple measurement error. While the condenser section showed notable temperature oscillations, the actual impact on heat removal performance was relatively small. The study concluded that periodic Geyser boiling had limited implications for the microreactor's performance. However, non-periodic Geyser boiling scenarios could have more significant consequences. Therefore, further research is needed to address this effect and ensure the safety and efficiency of heat pipe-cooled microreactors in various conditions.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No.2021M2D2A1A03048950).

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