

Experimental Investigation of Geyser Boiling Onset Based on Initial Liquid Pool Formation

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1. Introduction

A heat pipe is a passive device that transports heat through the phase change of a working fluid, enabling nearly isothermal operation with high effective thermal conductivity and no active components. This passivity and simplicity have made heat pipes attractive for microreactors. Heat pipe cooled microreactors (HPMRs) remove core heat passively through liquid-metal heat pipes embedded in a solid core. Several HPMR concepts have been developed, including eVinci and the Special Purpose Reactor (SPR). A preliminary assessment of the SPR indicates that orienting the heat pipes vertically yields higher operating margin than a horizontal configuration, suggesting that a vertical orientation is preferred [1].

However, in vertical orientation, a thermal-hydraulic instability known as geyser boiling can occur. When the liquid inventory exceeds the amount the wick can hold against gravity, the excess accumulates at the evaporator as a stagnant liquid pool [2]. As heat is supplied, superheat accumulates in the pool and is periodically released as vapor, producing temperature oscillations. These oscillations impose cyclic thermal stress on the heat pipe and can further induce core power fluctuations [3]. Therefore, geyser boiling threatens both component durability and reactor stability, and its operating conditions must be identified for safe operation.

Geyser boiling has accordingly been studied extensively, characterized in terms of design parameters such as inclination angle, filling ratio, and evaporator geometry, with the applied heating power [4, 5]. Despite these achievements, the results are specific to the heat pipe tested and are difficult to apply to other configurations. Rather, these parameters govern the amount of liquid that accumulates as a pool at the evaporator, which is the physical origin of the phenomenon. Therefore, these design parameters can be integrated into a single variable, the initial liquid pool height, which is estimated from a capillary-gravity balance within the wick [2] and adopted as the governing variable in this study, while the heat transfer rate remains an independent operating variable. The predicted pool height is used to interpret geyser boiling across inclination angles, with emphasis on the onset condition at which a pool first forms. The objective is to verify experimentally that the liquid pool height governs geyser boiling onset, providing a basis for a regime description that can ultimately be generalized across heat pipes.

2. Modeling and Methodology

2.1 Experimental Configuration

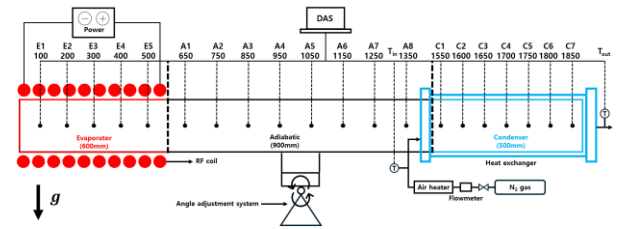


Fig. 1. Schematic of experimental configuration

Fig. 1 shows the schematic of experimental configuration. The evaporator was heated by RF induction, and the condenser was cooled by forced convection of nitrogen gas. The experimental conditions and heat pipe specifications are summarized in Table I.

Table I: Experimental conditions and heat pipe specifications

Experimental conditions	
Power	25 A, 5 A increment
Cooling	200 °C, 250 LPM
Inclination angle	15°, 19°, 22°, 30°
Heat pipe specifications	
Length	2000 mm
O.D. / I.D.	19.05 mm / 16.57 mm
Wick Type	Screen (#120, 12layer)
Effective pore radius	0.06 mm
Working Fluid	99.7 % pure Na
Filling amount	102 g (190 %)

2.2 Liquid Pool Length Prediction

The length of the liquid pool formed at the evaporator section can be predicted using the methodology proposed and verified by Huang et al. [2], which is derived from a capillary-gravity balance. From this balance, the liquid pool height is calculated from Eq. (1), where h_{cap} is the capillary height and $\frac{2\sigma}{r_{eff}}$ is the capillary pressure of the wick.

$$(1) L_{pool} = \frac{A_{wick}}{A_{vapor}} \left(L_{HP} - \frac{h_{cap}}{\sin \theta} \right), h_{cap} = \frac{2\sigma}{r_{eff} \rho_l g}$$

As shown in Fig. 2, a liquid pool is predicted to form at inclination angles above 19°. Therefore, this angle is defined as the onset angle for liquid pool formation.

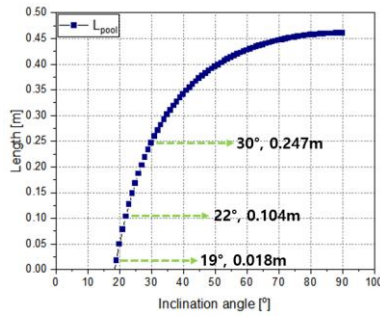


Fig. 2. Predicted liquid pool height

3. Results and Discussion

Fig. 3 shows the geyser boiling regime map in terms of the liquid pool height and heat transfer rate for inclination angles of 15°, 19°, 22°, and 30°. For the 15° case, selected as a test condition below the onset angle, no liquid pool formation was predicted, and no geyser boiling was observed over the entire power range. Geyser boiling phenomena occurred from 22°, where the liquid pool height was predicted to be 108 mm.

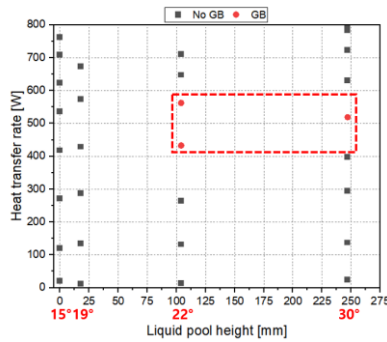


Fig. 3. Geyser boiling regime map

Fig. 4 shows the temperature oscillation at 22°. At E1 (100 mm), located below the predicted liquid pool, the temperature exhibits cyclic gradual rise followed by an abrupt drop, while the measurement points above E1 show sharp spikes from the incoming vapor burst. The gradual rise corresponds to superheat accumulation in the liquid pool, and the abrupt drop to the sudden vapor release that expels the liquid plug upward. The boundary between the two behaviors agreed with the predicted pool height, confirming that geyser boiling originates from the liquid pool.

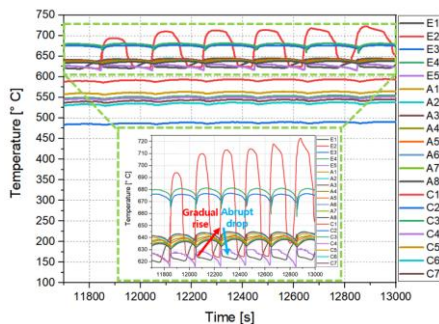


Fig. 4. Temperature oscillation at $q_s=562.2\text{W}$ at 22°

However, at 19°, a liquid pool of 18 mm was predicted, yet no geyser boiling was observed over the entire power range. This suggests that the presence of a liquid pool alone is not sufficient for geyser boiling and that a sufficiently large pool is required for onset, with the critical pool height for the present heat pipe lying between 18 and 108 mm. Further experiments at finer inclination intervals, such as 20° and 21°, with repeated measurements, are required to identify this threshold more precisely.

4. Conclusions

This study proposed the initial liquid pool height as a governing variable for geyser boiling onset and experimentally demonstrated its validity in a 2 m sodium heat pipe. Geyser boiling occurred at 22°, where a 108 mm pool was predicted, but not at 19°, where a smaller pool of 18 mm had already formed, indicating that a sufficiently large liquid pool is required for onset rather than its mere presence. By reframing the onset criterion in terms of the liquid pool height rather than design-specific parameters such as inclination angle and filling ratio, this study provides a consistent basis for comparing geyser boiling across heat pipes of different designs. It further offers a quantitative criterion for selecting the filling ratio and wick that keep the liquid pool below the onset level, thereby avoiding geyser boiling.

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