Experimental Investigation of Thermal Performance on Underfilled Annular Wick Sodium Heat Pipe

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1. Introduction

Recent severe accidents have raised interest in the passive safety of reactors, driving active development of compact reactor designs and reliable cooling technologies. In particular, the demand for energy in remote areas and specialized applications has accelerated research into microreactors. These systems emphasize inherent safety and simplified operation, aligning well with the design objectives of compact, passively cooled reactor systems.

A heat pipe is a passive heat transfer device that transports thermal energy through the phase change of a working fluid [1]. Due to its high heat transfer capacity and structural simplicity, it has gained attention as a potential cooling method for microreactors. The advantages have led to the advancement of the Heat Pipe Microreactor (HPMR) concept through various research and investments. Therefore, various types of HPMR, such as eVinci [2], and KRUSTY [3] have been developed.

While heat pipes are promising devices for microreactor cooling, the thermal performance of heat pipes depends on the filling ratio of the working fluid. When the filling ratio is maintained near the priming level (~100 %), the heat pipe can exhibit the designed performance. However, in actual reactor environments, high operating temperatures can cause deformation of the wick structure, potentially leading to unintended overfilled or underfilled conditions. In an overfilling state, the dry-out limit typically increases. However, once steady state operation is reached, excess liquid can accumulate at the condenser end, creating a large temperature gradient and reducing overall heat transfer performance [4]. In the case of underfilling operation, working fluid volume is smaller than the wick volume, which destabilizes liquid transport. Lack of working fluid can induce significant degradation of heat pipe performance due to dry-out. Although the filling ratio has significant effect on the performance of the heat pipe, experimental data on underfilled conditions is insufficient, leaving a significant gap in the understanding of heat pipe behavior under such circumstances [5].

This study investigates the thermal-hydraulic behavior of underfilled heat pipes through experimental analysis. Inclination angle is considered as a key parameter to evaluate its influence on operating performance. Main perspective of underfilling heat pipe is insufficient working fluid at evaporator. Inclination angle will provide gravitational driving force which helps fluid transport. This study provides a database of underfilling heat pipe thermal performance for enhancing operational stability and identifying optimal design conditions for underfilled heat pipes.

2. Experimental Setup

2.1 Heat pipe design parameter

Annular screen wick type sodium heat pipe was used in the experiment. Detailed specifications are provided in Table I. The heat pipe has an overall length of 2 m, and an outer diameter of 19.05 mm. Liquid transport is driven by capillary action generated by a three-layer, 120-mesh screen wick, inserted in an annular configuration. The envelope was fabricated from ASTM 316L stainless steel. The working fluid consists of 73.5 g of 99.7% pure sodium. The heat pipe is divided into an evaporator, adiabatic, and condenser, with lengths of 600 mm, 900 mm, and 500 mm, respectively.

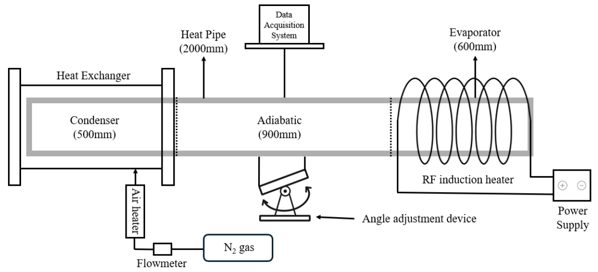
Table I: Heat pipe design parameter

	Parameter	Value
Envelope	Length	2000 mm
	O.D.	19.05 mm
	Wall thickness	1.24 mm
	Material	ASTM 316L
Wick	Type	Annular
	Annulus thickness	1.2 mm
	Wick thickness	0.54 mm
	Mesh	Screen (#120)
Working fluid	Material	99.7 % pure sodium
	Filling amount	73.5 g
	Filling state	Underfilling

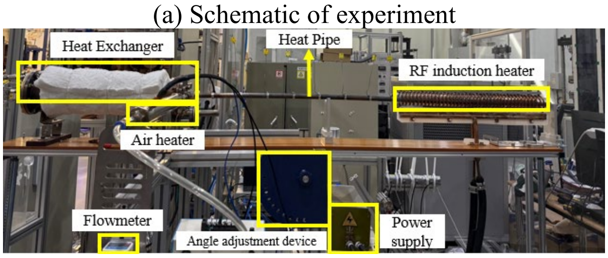
2.2 Experimental setup

A schematic of the experimental setup is shown in Fig. 1. The system consists of a radio-frequency (RF) induction heater, K-type thermocouples, infrared (IR) pyrometers, an air heater, a heat exchanger, and an angle adjustment device.

The angle adjustment device is positioned at the center of the heat pipe, allowing changes in operating angle for testing under different conditions. The heat pipe is cooled by a gas-cooled forced convection system. Nitrogen (N_2) gas is supplied to the heat exchanger located in the condenser section for cooling. Prior to operation, charged sodium may exist in a solid state. To eliminate its influence on startup, an air heater is installed at the heat exchanger inlet, enabling control of inlet temperature. In this study, the inlet temperature was set to 300 °C to ensure complete melting of sodium before operation.



(a) Schematic of experiment



(b) Experimental setup before insulating

Fig. 1. (a) Schematic and (b) Picture of experimental setup

Surface temperatures of the heat pipe are measured using K-type thermocouples. Seven thermocouples are placed along the condenser section at 50 mm intervals from 1500 mm, and eight are installed along the adiabatic section at 100 mm intervals from 750 mm. Additional thermocouples are placed at the coolant inlet and outlet. The evaporator temperature is measured using five IR pyrometers spaced 100 mm apart, starting 100 mm from evaporator end. The temperature is obtained from data acquisition system (DAS).

The experiments were conducted by varying inclination angles and increasing the RF induction heater power to observe the temperature response. The heat input was controlled by changing the current levels, starting from 20 A, and increasing by 3 A at each step. Steady state is defined when the temperature profile remains within a 5 °C range for 10 minutes, after which the input power is increased. Each test condition was conducted until the heat pipe reached its operating limit. The operating limit was defined when any point in the evaporator reached 900 °C. Experiments were performed at inclination angles of 0 °, 15 °, and 30 °.

3. Experiment Results

3.1 Horizontal orientation (0 °)

Fig. 2 presents the axial temperature distribution of the heat pipe under a horizontal (0 °) setting at varying power levels. Results show that the temperature of the evaporator increased with increasing input power, but nearly no change was observed in the adiabatic and condenser sections. The unchanged temperature in the adiabatic and condenser section indicates that insufficient working fluid reached the evaporator.

In an underfilled heat pipe, the limited fluid inventory leads to rapid dry-out. Therefore, stable operation requires a sufficient driving force to transport liquid to the evaporator. Under horizontal orientation, gravitational assistance is absent, leaving capillary force as the sole driving force. The annular wick used in the experiment has a mesh separated from the inner wall, forming an annular gap between the wick and the wall. Under underfilling conditions, annular geometry delays contact between the liquid and the wick, reducing capillary action. As a result, liquid supply to the evaporator becomes insufficient, and the overall heat transfer performance deteriorates. At a power level of 29 A, the evaporator peak temperature reached approximately 900 °C, marking the operating limit.

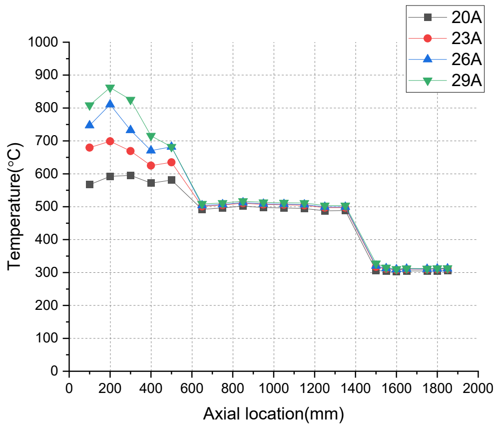


Fig. 2. Axial temperature distribution of horizontal orientation

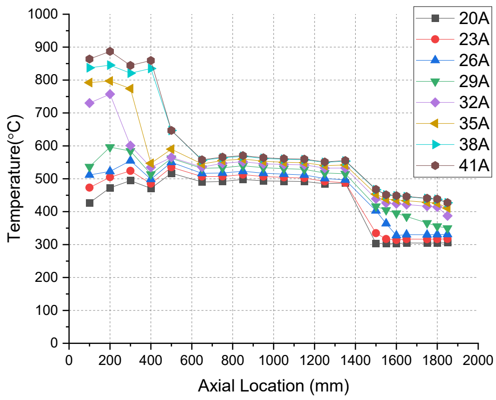
3.2 Inclined orientation (15 °, 30 °)

Fig. 3 shows the axial temperature distributions at inclination angles of 15 ° and 30 °, respectively. Both cases exhibited improved thermal performance compared to the horizontal orientation, due to gravity.

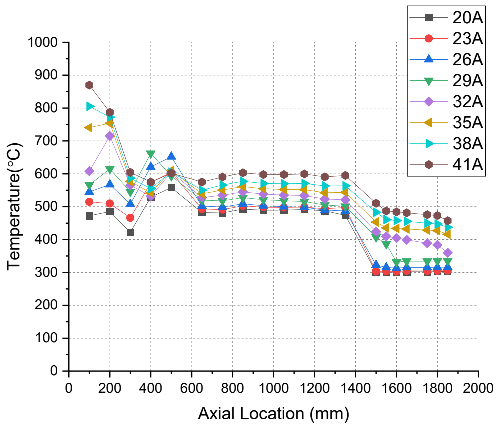
At 15 °, the adiabatic and condenser section temperatures gradually increased with rising power. Gravity enhanced fluid flow rate to the evaporator, extending the effective operating length and increasing the operation limit. Up to 29 A, it is considered that there is a liquid pool on the evaporator due to the lowest temperature at the end side. From 32 A, liquid pool evaporated, leading to a rapid temperature increase at the end of the evaporator.

At 30 °, the adiabatic and condenser sections showed larger temperature increases compared to the 15 ° case, as the stronger gravitational effect also promoted the formation of a larger liquid pool. After 32 A, the behavior diverged from the 15 ° case. While the 15 ° condition maintained a relatively uniform evaporator temperature after pool evaporation, the 30 ° setting exhibited a significant temperature gradient which was induced by geyser boiling. Due to the geyser boiling phenomenon, temperature oscillations were observed in the evaporator section as shown in Fig. 4. Intense vapor generation from the liquid pool disrupted liquid transport, resulting in partial dry-out and a rapid temperature rise at the evaporator end.

In the case of inclined orientation, the liquid pool initially lowers temperature at the evaporator end, and once the pool evaporates, local temperatures rise rapidly. At higher inclination, the larger pool leads to thermal non-uniformity, showing that liquid pool significantly affects thermal performance depending on operating conditions.

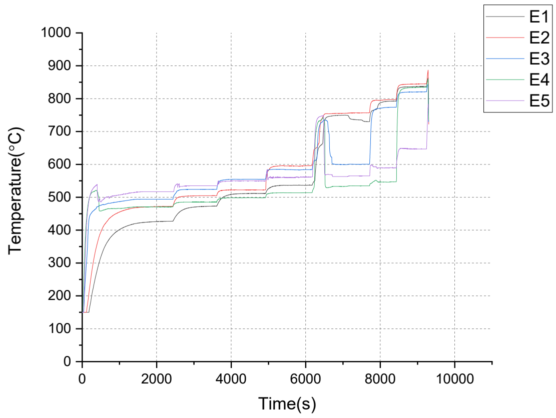


(a) 15 °

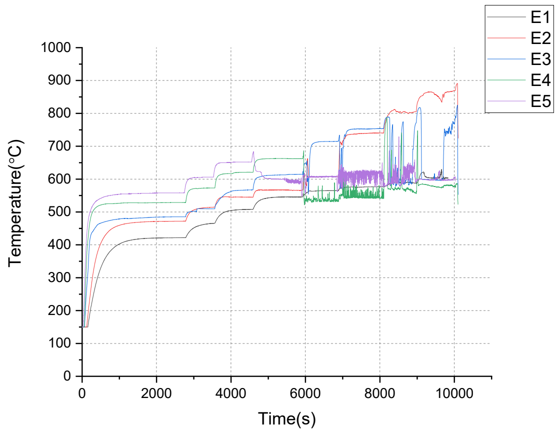


(b) 30 °

Fig. 3. Axial temperature distribution of inclined orientation



(a) 15 °



(b) 30 °

Fig. 4. Temperature distribution of evaporator

4. Conclusion and Future Works

In this study, the thermal performance of an underfilled heat pipe was experimentally evaluated under varying inclination angles. The results showed improved performance at inclined orientations compared to the horizontal case. The enhancement is attributed to gravitational assistance, which promotes greater liquid return to the evaporator and delays dry-out.

However, increasing inclination also led to the formation of a liquid pool at the evaporator end, which delayed startup, induced a temperature gradient in the evaporator, and triggered geyser boiling phenomenon. Future work will focus on identifying optimal operating conditions that enhance thermal performance while minimizing the adverse thermal effects associated with liquid pooling. Experiments will cover a wider range of inclination angles and incorporate additional variables such as wick structure. Furthermore, the experimental results obtained in this study expand the database for underfilled heat pipe behavior, providing baseline knowledge essential for the design and evaluation of reactor heat pipe systems.

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