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Effect of Screen Mesh Size on Thermal Performance of a 2 m Underfilled Annular Sodium Heat Pipe

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1. Introduction

Recent severe accidents have renewed interest in passive safety and compact reactor designs, leading to the development of microreactor systems and reliable passive cooling systems like heat pipe. For stable heat pipe operation in such systems, continuous two-phase circulation must be maintained. When liquid return to the evaporator is insufficient, dry-out occurs, and performance rapidly degrades. Therefore, the capillary limit is a critical factor governing the wick's ability to sustain liquid return.

In screen mesh wick, which is widely used for sodium heat pipes, capillary pumping capability increases as mesh size becomes finer due to reduced pore radius. However, finer meshes also decrease permeability and increase liquid pressure loss, making wick optimization challenging in long heat pipes.

Annular screen wick structures mitigate this issue by additional liquid channel that reduce pressure loss while preserving capillary pressure. Previous studies have demonstrated higher capillary limits and improved thermal performance for annular configurations [1, 2].

In addition, this study focuses on underfilled heat pipe conditions. Underfilling reduces the available liquid inventory, accelerating dry-out and increasing axial temperature gradients. According to 2025 PIRT for Heat Pipes [3], underfilling is identified as a key factor influencing performance degradation, startup failure, and premature dry-out. Despite its significance, experimental studies under underfilled conditions remain limited, particularly under varying boundary conditions and wick configurations.

Therefore, this study examines the effect of screen mesh size on a 2 m annular sodium heat pipe under underfilled conditions, focusing on the interaction between capillary pumping and permeability.

2. Modeling and Methodology

2.1 Annular Screen Wick Sodium Heat Pipe

Table 1 summarizes the detailed specifications of the sodium heat pipes employed in this study. Sodium was charged as working fluid, and both HP-120 and HP-250 were filled as underfilled conditions.

Table I: Heat Pipe Design

	HP-120	**HP-250**
	Pipe	
Length	2000 mm	
O.D.	19.05 mm	
I.D	16.57 mm	
	Wick	
Type	Annular screen	
Annular gap	1.2 mm	
Wick layer	3 layer of screen mesh	
Mesh size	# 120	# 250
Pore radius	0.105 mm	0.05 mm
Porosity	0.634	0.675
Permeability	1.38E-10 m^2	3.83E-11 m^2
	Working Fluid	
Material	99.7 % pure Na	
Filling amount	73.5 g (72 %)	82.7 g (80.1 %)
Filling state	Underfilled	

2.2 Experimental Apparatus

Fig. 1 illustrates the experimental setup, which consisted of an RF induction heater, a gas-cooled heat exchanger, and an air preheater. The sodium heat pipe was heated by RF induction, with input power controlled by adjusting the coil current from 20 A in 3 A increments. At each step, steady state was reached before increasing the power, and experiment was ended when the wall temperature approached around 900 °C. The condenser was cooled by nitrogen gas preheated to 200 °C and supplied at 500 LPM to ensure stable operation.

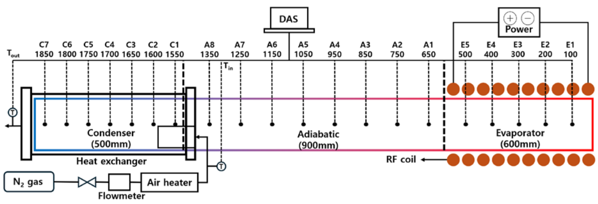


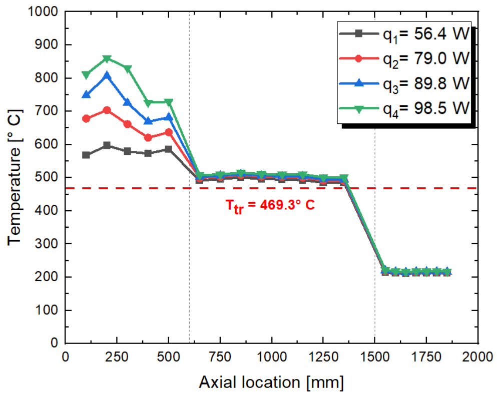
Fig. 1. Schematic of Experiment Setup

2.3 Heat Pipe Activation

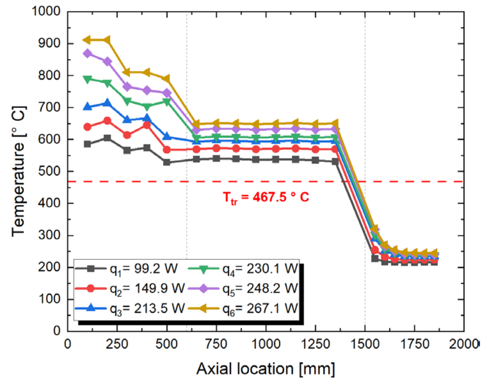
To determine heat pipe activation at each point, the Knudsen number (Kn) was evaluated. When Kn < 0.01, the vapor enters the continuum flow regime, enabling efficient axial heat transfer within the heat pipe. The transition temperatures corresponding to the continuum regime were calculated to be 469.3 °C and 467.5 °C for HP-120 and HP-250, respectively [4, 5].

3. Result and Discussion

3.1 Temperature Distribution and Activation Behavior



(a) HP-120



(b) HP-250

Fig. 2. Steady state temperature distribution

Fig. 2(a) shows the axial temperature distribution of HP-120. Significant temperature gradients were observed at the evaporator and condenser sections. As heat input increased, only the evaporator temperature rose, while the adiabatic and condenser sections showed minimal change. Although the adiabatic section exceeded the transition temperature, the condenser remained below it, indicating insufficient vapor generation. This behavior is attributed to the annular wick geometry. Under underfilled conditions, most of the working fluid accumulates in the annular channel, leaving the wick partially wet and limiting capillary-driven liquid return. Consequently, liquid supply to the evaporator is restricted, leading to continuous temperature rise and eventual dry-out.

Fig. 2(b) presents the temperature distribution of HP-250. Similar to HP-120, axial temperature gradients were observed. However, HP-250 showed temperature increases in the adiabatic and condenser sections as heat input increased. Although the condenser temperature remained below the transition temperature, the reduced axial temperature non-uniformity suggests that the heat pipe was approaching activation.

Despite the reduced permeability associated with the finer mesh, HP-250 exhibited improved thermal behavior compared to HP-120. This indicates that the enhanced capillary pumping capability played a more dominant role in liquid return within the annular wick. Consequently, the axial temperature gradient was mitigated, enabling operation up to the higher heat-input condition of q_6.

4. Conclusions

This study examined the influence of screen mesh size on a 2 m annular sodium heat pipe under underfilled conditions. HP-120 exhibited large axial temperature gradients, with activation limited to the adiabatic section due to restricted liquid return and insufficient vapor generation. In contrast, HP-250 showed improved thermal response, with temperature increases extending toward the condenser as heat input increased. Despite reduced permeability, the finer mesh enhanced capillary-driven liquid return, mitigating temperature gradients and enabling operation at higher heat input.

These findings demonstrate the combined effect of mesh size, capillary pressure, and permeability in long annular wick heat pipes, particularly under limited liquid inventory conditions. The results provide useful guidance for wick optimization in long sodium heat pipes for microreactor applications. However, since the present study was limited to specific filling ratios and mesh sizes, further investigation with higher liquid charge and finer mesh structures is necessary to establish optimal operating conditions.

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