Development and Preliminary Testing of 3D-Printed Sodium Heat Pipe with Groove Wick

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1. Introduction

A heat pipe is a passive heat transfer device that utilizes two-phase flow and latent heat as mode of heat transport [1]. It consists of a closed tube with a wick structure attached to the inner wall and filled with a working fluid.

3D-printing technology such as additive manufacturing (AM) opens possibility for a complex wick structure or bent heat pipe. AM has been on the rise for heat pipe manufacturing and several studies on the characterization of AM heat pipes [2-4] has been done. Park and Bang [5], and Lee and Bang [6], demonstrated the feasibility of fabricating 3D-printed heat pipes using AM method and outlined the operational limits based on wick structure and manufacturing conditions. Our previous work continuing that study [7], tested the AM heat pipe charged with water to check the sealing and thermal performance of the heat pipe.

The current study was to develop a 3D-printed heat pipe and fill it with sodium and preliminary tested the heat pipe with several power levels to see its thermal behavior and efficiency.

2. Experimental setup

2.1. 3D-printed heat pipe

Table I: Design parameters of 3D-printed sodium heat pipe

Parameters	**Value**
Total length (mm)	300
Evaporator/adiabatic/condenser length (mm)	100/100/100
Outer radius (mm)	9.5
Inner radius (mm)	8.5
Groove depth (mm)	0.8
Groove width (mm)	0.6
Number of grooves	35
Filling ratio (%wick volume)	100 (6 g sodium)

The heat pipe used in this study is a groove heat pipe which was manufactured via AM from SS316L powder which was mentioned in previous study [3–4, 6–7]. The design adopts a groove-wick configuration, in which axial grooves are integrated into the inner wall of the pipe during the 3D-printing process as shown in Table I. After ultrasonic cleaning, the heat pipe was dried at 70 °C for 1.5 hours to remove moisture, then vacuum tested for leaks. It was filled with high purity sodium; the filling ratio was calculated based on 100% of wick volume rather than the evaporator volume. Then the heat pipe was degassed at 150 °C under vacuum and finally sealed by crimp welding.

2.2. Experimental set-up

The experimental setup consists of cartridge heater, the 3D-printed sodium heat pipe with horizontal orientation, cooling jacket, and data acquisition system (DAQ). In total there are 10 thermocouples used to measure temperature in this study.

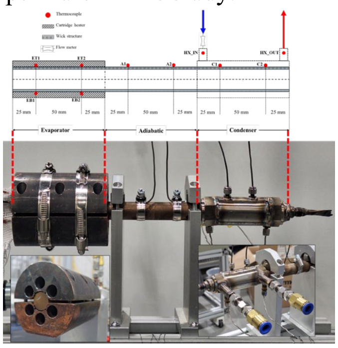

Fig. 1. Experimental setup of 3D-printed sodium heat pipe

The thermocouples are spaced evenly (2.5 cm) from the beginning and end of each section. For evaporator section, thermocouples are located on top and bottom to track whether the dry-out has occurred. Due to the geometry of the cartridge heater channel (shown in Fig. 1.) the thermocouples are located co-axially 90 degrees between each other. The thermocouple's locations and experimental setup are shown on Fig. 1. The entire setup then was insulated with ceramic wool to minimize heat loss to the environment. The cooling jacket utilizes nitrogen (N_2) to cool the condenser section. The power output was calculated by the difference of temperature between the heat exchanger inlet and outlet.

3. Results and Discussion

Fig .2 illustrates the physical transient process of the heat pipe from cold startup to semi-steady state operation. There are 5 power levels applied to the heat pipe with each power level being held for around 1 hour. This period was taken initially because we consider it is enough time to reach steady state, as calculated there was no significant change in temperature (<1% deviation). The initial test starts with 300 W of power; the sodium was frozen and started to melt at around 97.8 °C. There is a noticeable temperature difference between the heat pipe section which indicates either the heat pipe reached its operational limit or the heat pipe is underfilled.

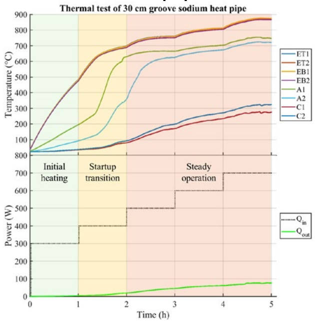

Fig. 2. Transient temperature profile of the heat pipe

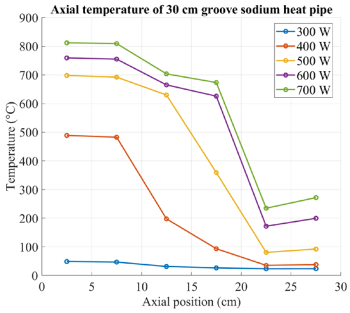

Fig. 3. Axial temperature profile for each power level

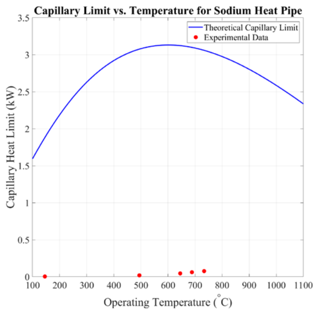

Fig. 4. Capillary limit and current heat pipe operational state

The difference in temperature can be seen better in Fig. 3, where there is a gap at later power level in the steady state temperature of each section. At the later power level, the temperature difference from the ET1 and C2 reached 548.4 °C. There are several possible reasons for this kind of behavior, one is capillary limitation of the heat pipe and the second is underfilled heat pipe. We calculated the estimated capillary limit of the heat pipe and plotted the power output as shown in Fig. 4, which our heat pipe is far below the capillary limit. So, the other possible cause and the most probable one is caused by underfilling the heat pipe, and this is in fact a common case in groove heat pipe. Additionally, due to the size of the cooling jacket, the two thermocouples at the condenser end couldn't be secured properly on the heat pipe wall that might cause the reading shown in Fig. 2 C1 and C2 temperature.

4. Conclusions & Future work

The manufacturing process and experimental study conducted on the 3D-printed sodium groove heat pipe demonstrated several key findings related to its performance:

1. The 3D-printed sodium heat pipe was successfully charged and thermal tested with rigorous pre-manufacture and vacuum tests.
2. The heat pipe thermal test showed an underfilled heat pipe behavior where there was a significant temperature gap between the evaporator and condenser region.
3. Filling ratio calculation for groove heat pipe should be adjusted to other means such as evaporator void volume.

The present study established and demonstrated the overall manufacturing workflow for a 3D-printed sodium heat pipe. Future work will focus on optimizing performance by investigating alternative wick structures and filling ratios and extending the manufacturing and test campaign to longer sodium heat pipes.

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