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Exploring the feasibility of 3D-printed high-temperature heat pipe for nuclear reactor application: seal testing and water charged thermal cycling evaluation

Almanzo Arjuna, Faruk Celik, Dong Hun Lee, In Cheol Bang
Department of Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST)
50 UNIST-gil, Ulju-gun, Ulsan, 44919, Republic of Korea
**Corresponding author: icbang@unist.ac.kr*

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1. Introduction

Recent trends in heat pipe micro reactor (HPMR) development create an urgency to ensure a safe design of the reactor. In terms of cooling HPMR uses heat pipe to transfer the heat generated in its core. A heat pipe is a two-phase device that can transfer heat with a high heat rate with low temperature difference which utilize phase-change [1]. The HPMR core usually is a monolith core design with multiple fuel rods and heat pipes welded into a matrix. Various types of HPMR, such as eVinci [2], Megapower [3], ANTARES R1 [4], and Kilopower [5] are being actively developed.

For proper thermal performance of heat pipe operation, proper material, wick structure, and charging are required. The material selection should consider the working fluid and operational conditions of the heat pipe, in addition in later stage due to harsh neutron irradiation during nuclear reactor operation, following consequences should be considered. The wick structure is a component in a heat pipe which affect the capillary action – primary mode of heat pipe operation. High capillary action means better circulation of fluid inside the heat pipe. Charging is a critical factor in heat pipe performance, as the purity of the working fluid directly impacts capillary action and long-term reliability. Minimizing impurities will enhance capillary forces within the wick structure, ensuring efficient fluid circulation and sustained thermal performance.

To integrate heat pipes into a HPMR, several aspects must be considered during designing and fabrication. Heat pipe geometry should allow space utilization as HPMR is aimed to be compact and transportable for some. Bending in the final design might be inevitable, to conserve space for other components. Using three-dimensional (3D)-printing technology opens possibility for a complex wick structure or bent heat pipes geometry without compromising the integrity of the heat pipe compared to manual manufacturing. Recent studies have been conducted on 3D-printed heat pipes manufacture. Lee et al [6], demonstrated the feasibility of fabricating 3D-printed heat pipes using additive manufacturing (AM) method and outlined the operational limits based on wick structure and manufacturing conditions. The study also emphasizes the need for further thermal performance evaluation and productivity assessments to determine the viability of 3D-printed heat pipes for real-world applications. Park et al [7], successfully fabricated and tested a bent heat pipe with a complex wick design. The results indicated that the combination of screen and groove wicks at different sections of the heat pipe significantly enhanced capillary pumping capability. Additionally, Celik et al [8] investigated the effect of filling ratio on the entrainment limit of a large-scale heat pipe with a 3D-printed wick structure. The study worked on a 4-meter-long water heat pipe, a larger scale than previous study. The work suggests that a higher filling ratio resulted in better thermal management and delayed the onset of entrainment.

Due to its process, it’s hard to get high-quality and structurally sound AM 3D-printing results. Inner porosity inside the heat pipe wall may cause an increase of volume and additional thermal resistance in heat pipe operation. In addition, welding which are used to connect each heat pipe segment may impose leakage. Chen et al [9] manufactured an oscillating heat pipe (OHP) via AM method. The study several tests to ensure the heat pipe seal integrity and thermal performance were done, including scanning electron microscope (SEM) imaging, internal structure CT scan, positive and negative pressure leak test, and heat transfer experiment. These rigorous steps are being taken to ensure the integrity of the 3D-printed heat pipe.

Building on this foundation, the present study will explore the feasibility of 3D-printed high-temperature. Ensuring the seal integrity of the 3D-printed heat pipe to ensure vacuum tightness is important. To further explore this, the current study will conduct vacuum seal testing and water-charged thermal cycling test. By addressing these aspects, this research aims to further build on previous work [6], [7], [8] and contribute to the development of heat pipe micro reactors.

2. Experiment

2.1. 3D-printed heat pipe

As mentioned previously, the experiment utilizes 3D-printed heat pipe mentioned in [6] which was fabricated using AM. This heat pipe features a grooved wick design. This type of wick has been actively studied for use in microgravity environments such as spacecraft. One limitation of grooved wicks is their lower capillary pumping capability compared to sintered or mesh wicks. However, it can be improved by using AM technology, which can customize surface roughness or by simply adding a screen mesh.

The heat pipe in this study itself is using 316 stainless steel (SS316L), a material that is commonly used for microreactor sodium heat pipes due to its excellent neutron cross-section and thermal conductivity. For this current study, a 300 mm heat pipe was chosen, because of the current AM technology limitations, such as limited build volume of 3D-printers and thermal deformation during printing longer parts. The final goal of this study is to fabricate a liquid metal heat pipe with a screen-grooved wick using AM technology. The heat pipe cross section design is shown in Fig. 1, and further design parameters can be seen in Table I.

Table I: 3D-Printed heat pipe parameters

Parameters	**Value**
Total length (mm)	300
Evaporator/Adiabatic/Condenser length (mm)	100/100/100
Outer radius (mm)	9.5
Inner radius (mm)	8.5
Wick type	Grooved
Groove depth (mm)	0.8
Groove width (mm)	0.6
Number of grooves	35
Theoretical volume (mm^3)	54245
Material	SS316L

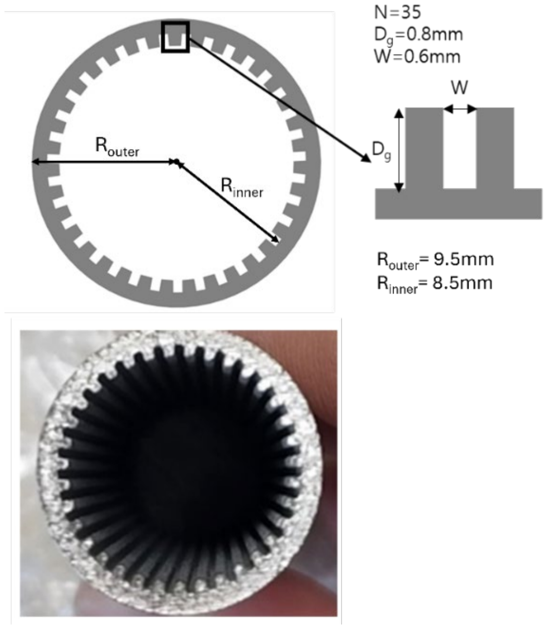
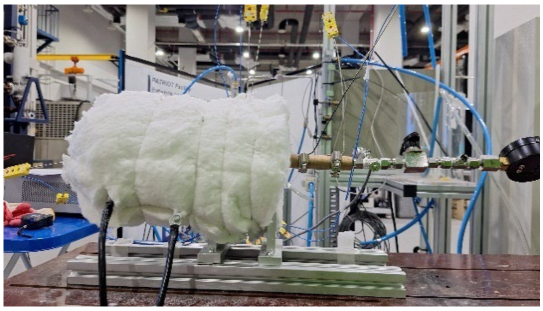


Fig. 1. 3D-printed heat pipe cross-section

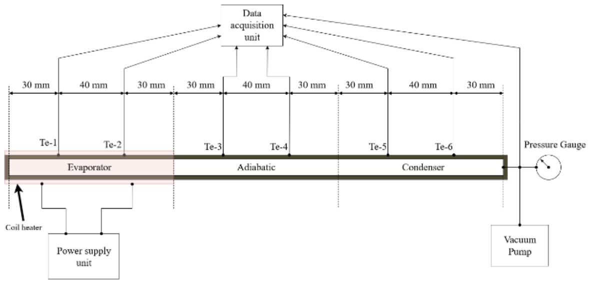
2.2. Experimental set-up

The experimental study was conducted to analyze the seal integrity and water-charged performance of the 3D-printed heat pipe. A simple experimental set-up has been built and consisted of 3D-printed heat pipe, a heating system which utilizes coil heater, vacuum pumping system, and data acquisition unit. The experimental set-up is shown in Fig. 2a. To heat the evaporator part, we utilize a coil heater which is connected to a power supply. The system was depressurized to 41.2512 kPa, which was the limit of our current vacuum pump. The condenser was cooled by a natural convection.

There are two experiments done, the first with an empty heat pipe and the second with 100% filling ratio (FR, $V_{fluid}/V_{evaporator}$) water charged heat pipe. There are a total of six thermocouples that were utilized in the system, two in each evaporator, adiabatic, and condenser section. Additionally, one pressure transmitter was attached at the end of the condenser section as shown in Fig. 2b.



(a)



(b)

Fig. 2. (a) Actual experimental setup and (b) Schematic diagram of experimental apparatus

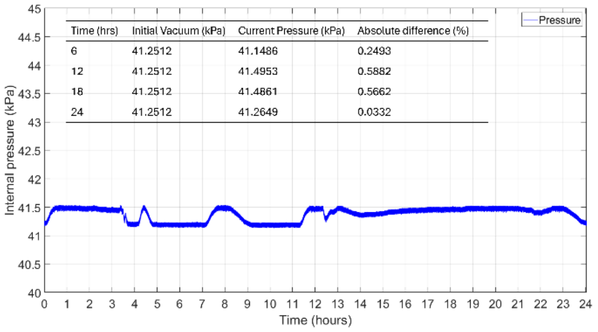
The thermocouples were located similarly for each section, one is located 3 cm from the beginning of the section and the other is located 3 cm from the end of the section (4 cm apart from each thermosyphon in a section) as shown in Fig. 2b.

3. Results and Discussion

3.1. Vacuum seal test

The first seal test was a low-pressure seal test, with an empty heat pipe. The heat pipe initially was in room temperature and vacuumed to 41.2512 kPa, then the valve at the end of the heat pipe was closed. The pressure levels were continuously monitored over 24 hours to verify the seal integrity of the 3d-printed heat pipe. The results of the test are shown in Fig. 3.

Based on the test results, it was found that the 3D-printed heat pipe holds its seal integrity and was able to withstand low pressure conditions for an extended period of time. Some fluctuations may occur due to measurement sensitivity and minor temperature fluctuations rather than actual leakage. Further long-term testing or a helium leak test will be done to further validate this work.

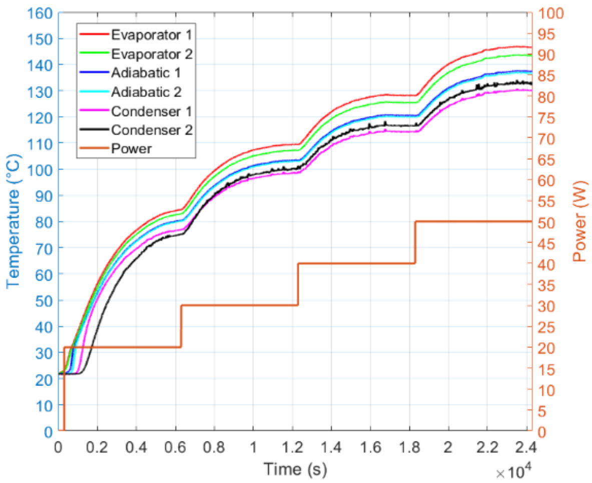


Time (hrs)	Initial Vacuum (kPa)	Current Pressure (kPa)	Absolute difference (%)
6	41.2512	41.1486	0.2493
12	41.2512	41.4953	0.5882
18	41.2512	41.4861	0.5662
24	41.2512	41.2649	0.0332

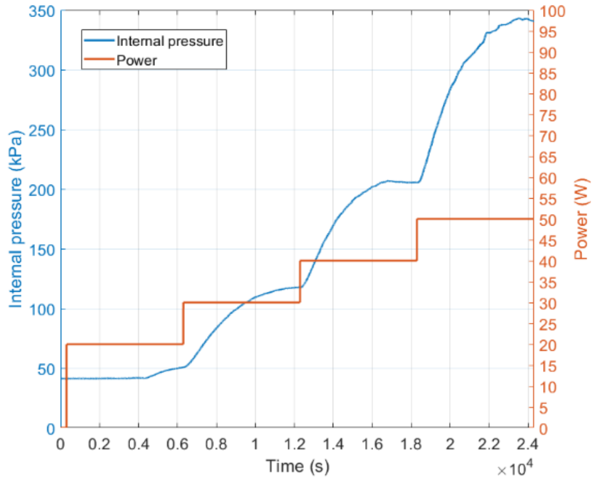
Fig. 3. Pressure profile during low-pressure seal test

3.2. Water charged thermal cycle test

The second test was a thermal cycling test, the 3D-printed heat pipe was charged with water (100% FR). All sections of heat pipe initially were at room temperature, the power was then incrementally increased through 4 power levels: 20 W, 30W, 40 W and 50 W, with a period of 100 minutes each. 100 mins were taken as the heating period because there was no significant change in temperature (<1 %) and pressure (<2%) for about 5 minutes. Throughout the process, temperature, pressure, and power inputs were being closely monitored. The temperature and pressure over time are represented in Fig. 4a and 4b, respectively.



(a)



(b)

Fig. 4. (a) Temperature and (b) Pressure evolution for thermal cycle evaluation

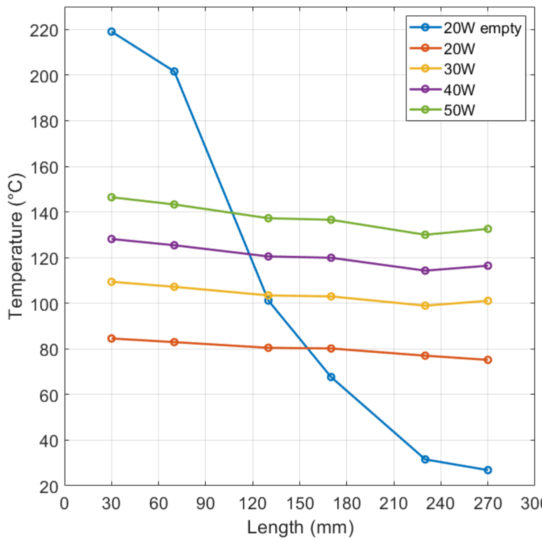


Fig. 5. Steady state temperature for every power level along the heat pipe length

As expected, the overall temperature for evaporator is higher than the adiabatic, and the adiabatic is higher than the condenser. An interesting thing happens at around 7200s where the temperature for condenser 2 gets higher than the condenser 1. While insufficient cooling may play a role, another possible explanation is vapor accumulation and pressure build-up at the condenser end, which locally increase the temperature. Additionally, wick limitations, where an imbalance in liquid return could cause localized dry-out at that spot. This effect can be seen more clearly in Fig. 5. Given the relatively short length of the heat pipe (30 cm), conduction may affect the temperature of the condenser. We also investigated the potential effect of conduction as well by heating up the empty heat pipe with 20W of power, but the results suggest that conduction is not a significant factor as shown in Fig. 5.

Thermal resistance can be calculated by dividing the average temperature difference of evaporator and condenser by the heating power.

$$R = \frac{T_e - T_c}{Q} \quad (1)$$

Thermal resistance with respect to heating power can be seen on Fig. 6.

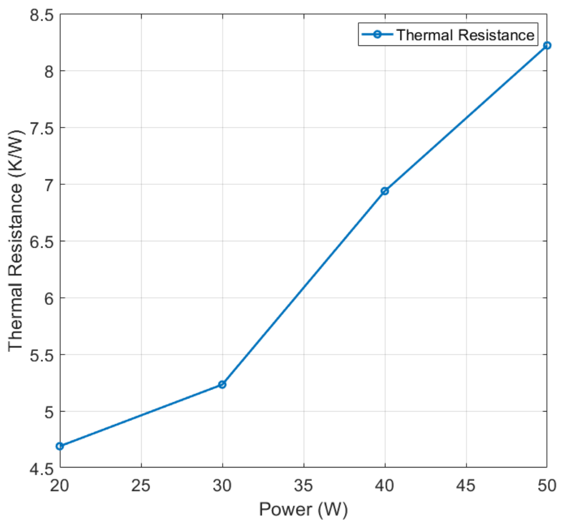


Fig. 6. Thermal resistance of the 3D-printed heat pipe

The increase in thermal resistance with increase with power is expected, but the sharp rise from 30 W to 40 W may suggest that the heat pipe may be approaching its operational limits.

4. Conclusions & Future Work

The experimental study conducted on the Additive Manufactured (AM) 3D-printed heat pipe demonstrated several key findings related to its performance:

1. Low-pressure seal test showed that the 3D-printed heat pipe successfully maintained its seal integrity under low pressure conditions (41.2512 kPa) for extended periods. This indicates that the AM process used to fabricate the heat pipe did not compromise its vacuum seal.
2. Thermal cycling test with 100% filling ratio (FR) revealed expected temperature distribution across heat pipe. There is temperature build up at the condenser end which was caused by vapor buildup.
3. The thermal resistance of the heat pipe was calculated and found to increase with the power input. While this is expected, sharp increase of the thermal resistance from 30 W to 40 W may indicate thermal limits of this configuration.

AM has proven itself to be a versatile technology that offers flexibility for a complex heat pipe design. This study serves as a preliminary study for the application of 3D-printed high temperature heat pipes for nuclear reactor application. Future testing includes testing with a lower pressure condition (in the order of 1.33 Pa/ 10^{-3} torr), CT scan to check the closed and open porosity and tests at higher heating input (in the order of 100s W) with sodium as the working fluid has been planned and will be done in the future.

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