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Experimental investigation of overfilled sodium heat pipe with different orientation

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1. Introduction

A heat pipe is a high-efficiency heat transfer device that utilizes the phase change of the working fluid in a sealed envelope. Heat pipes can transfer the large heat of phase change that maintain isothermal temperature over long distances, which can remove or reduce the moving parts of the system due to its passive characteristic. Liquid metal heat pipes are typically used in microreactors such as Westinghouse's eVinci [1] and Oklo power's Aurora [2] that have the advantage of using heat pipes as the primary cooling device to transfer heat from the core to the heat exchanger. Even in accident conditions, heat pipes ensure cooling performance to transfer decay heat. Heat pipes have the complexity of phase-change and capillary flow in a closed envelope, the performance of a heat pipe depends on several factors. In addition, liquid metal heat pipes usually start operating in a frozen state. Therefore, study about liquid metal heat pipes contains a wide temperature range from startup to maximum heat transfer and heat transfer limit models are evaluated to design the liquid metal heat pipes for system applications. [3]. Due to the properties of liquid metals, major concerns are sonic, entrainment, and capillary limitations. The sonic limit is related to the successful starting without choking of vapor flow, and the capillary and entrainment limit is related to the maximum heat transfer capacity without dry out of evaporator. Typically, hundreds of heat pipes are inserted in the microreactor core, as one heat pipe reaches its limit, it affects adjacent heat pipes which is one of the major accident scenarios in microreactors called 'cascade failure'. Therefore, it is important for microreactor to evaluate and understand the thermal behavior of liquid metal heat pipes close to limitations for its safety. Some researchers investigated the operating limitations of liquid metal heat pipes by changing several influencing factors and compared the results with conventional models. [4-5] However, previous experiments with liquid metal heat pipes have been performed close to or less than 100% of the filling ratio. The filling ratio can affect the performance of the heat pipe both at startup and maximum capacity. Previous literatures describe that a more amount of working fluid needs more time to startup, however, can increase the maximum capacity due to delay the dry-out phenomenon. To expand the understanding of the effect of filling amount, in this paper, we evaluated the thermal behavior of liquid metal heat pipes that fill the working fluid more than the pore volume of the wick. To analyze the effect of overfill on the thermal behavior of liquid metal heat pipe, a screen mesh heat pipe with a fill ratio of approximately 260% of the void wick volume was fabricated and tested. This paper deals with the operating range from 20 to 600 to evaluate the startup behavior and the steady-state performance. The further study will cover the heat transfer limitation conditions.

2. Experimental setup and overfilled sodium heat pipe

The length of the pipe is 900mm and the outer diameter is 19.05mm, and the capillary action is sufficiently designed by inserting 6 layers of #120 mesh. In this paper, 59.4 g of 99.7% pure sodium was filled into the heat pipe to indicate an overfilled condition of the sodium heat pipe. The filling ratio is determined by the ratio of the amount of the working fluid to the volume of the wick (1).

$$\text{Filling Ratio} = \frac{\text{Sodium Volume}}{\text{Wick Void Volume}} = \frac{m_s / \rho_s(T)}{\varepsilon L \dfrac{\pi(D_w^2 - D_v^2)}{4}} \quad (1)$$

The configuration of the experimental setup is shown in Fig 1. The power source selected RF induction heating method. High heat pipe temperatures can be achieved, and a variety of boundary conditions can be investigated. The RF induction heater can transfer 40 kW of power at a nominal 50 kHz frequency and the power level was controlled with a current of 10 A to 100 A. Six K-type thermocouples were installed at an interval of 100 mm to measure the temperature, since induction heating is a method of generating heat inside the metal, an IR thermometer was used to observe the temperature of the evaporator to avoid indirect heating of the thermocouple as shown in Fig. 2. This paper deals the horizontal and vertical orientation.

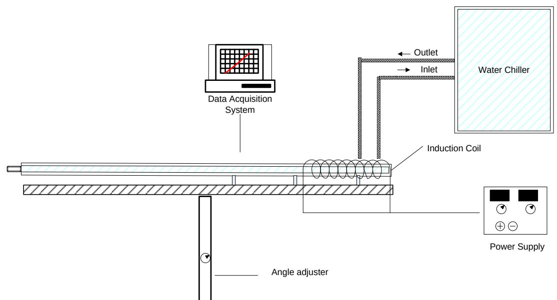


Fig. 1. Schematic of liquid metal heat pipe experiment

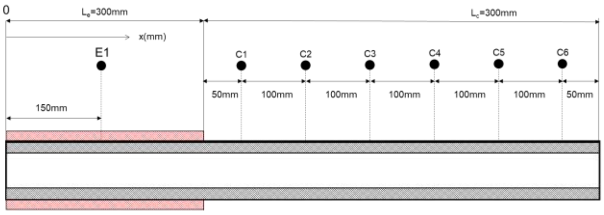


Fig. 2. Schematic of temperature measurement point of experiment setup

3. Results and discussions

Fig 3 and 4. represents the temperature behavior in the 20 to 600 range under horizontal conditions of an overfilled heat pipe. Because the boiling point of sodium is as high, in the initial behavior, only the temperature of the evaporator rises like a simple metal rod. Although power increases, the amount of sodium vapor present inside the heat pipe is small in this condition, the viscous limit region is observed that heat input only raises the temperature of the evaporator.

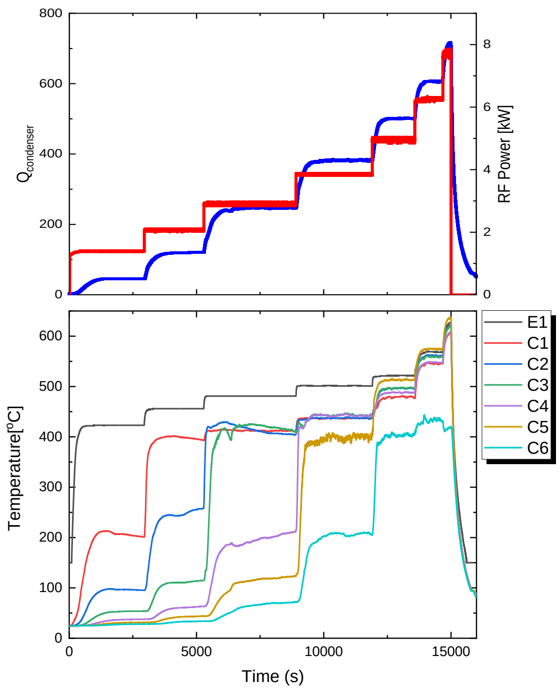


Fig. 3. Temperature behavior from startup to steady state of horizontal condition

It was confirmed that the increase in the amount of heat input after entering the continuous flow region leads to heat transfer from the evaporator to the condenser resulting in an almost isothermal temperature difference (ΔT<10°C). This is a typical characteristic of a heat pipe in which the temperature remains almost isothermal due to the passive liquid transport by capillary action according to the phase change. And the significant decrease in temperature at high power (QRF=7.7 kW) occurred. That is a partial entrainment phenomenon that the sound of the droplet impact is evidence of it. The sodium droplets are entrained in part due to shear forces at the interface between the vapor and liquid moving in opposite directions (evaporator to condenser), and these entrained droplets collide with the wall and produce a sound. Dry-out of the evaporator was not observed even under partial entrainment. It means that an overfilled heat pipe is sufficient to maintain heat transfer performance even if partial entrainment occurs. The reason for the drop in temperature at C6 is that the entrained droplets constantly collide at the end of the wall and this extra liquid does not participate in the fluid circulation by the capillary and forms a pool of liquid at the end of the condenser and this liquid pool need more superheat to become vapor. If the thermal power is further increased, more liquid sodium will be present due to the collision of the droplets, which will lower the temperature of C6.

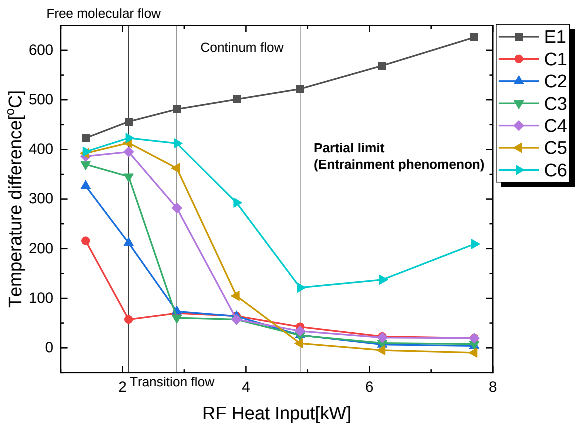
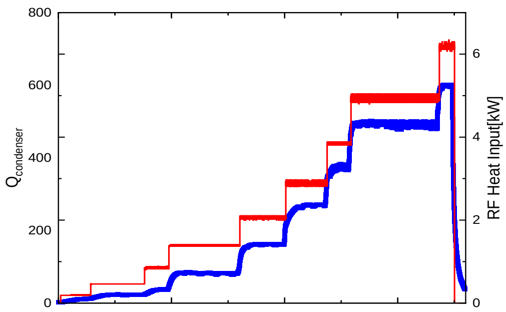


Fig. 4. Temperature behavior from startup to steady state of horizontal condition

The experimental results of the vertical operation are shown in Fig. 4. Frozen state, viscous limit, and continuum flow regime appeared with increasing heat input similar to the horizontal condition. As it enters the continuum flow, the temperature of the entire heat pipe rises. Under the influence of gravity and capillary forces, liquid transportation is enhanced resulting in an almost isothermal temperature difference ($\Delta T < 49°C$) from the heating section to the condenser end compared to horizontal operating conditions.



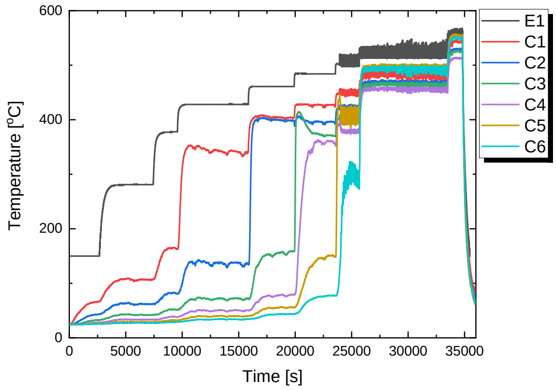


Fig. 5. Temperature behavior from startup to steady state of horizontal condition

Since a liquid pool is formed in the heating part in horizontal orientation, a geyser boiling phenomenon that a pattern of repeated temperature fluctuations after a certain power (QRF=3.8kW), appears. The overfilling condition may be prone to the formation of a liquid pool in the evaporator region, nucleation boiling occurs depending on the superheating degree of the liquid pool, and bubble growth and escape of the liquid pool cause temperature fluctuations. Also, the partial entertainment that occurred in the horizontal condition at the same heat input condition did not occur in the vertical condition, because gravity helps the fluid circulate and has a higher heat transfer limit condition.

In the future, since it is easy to form a liquid pool under vertical conditions, we plan to experiment with phenomena near the operating limit caused by pool formation such as nucleate boiling and geyser boiling under higher heat input conditions.

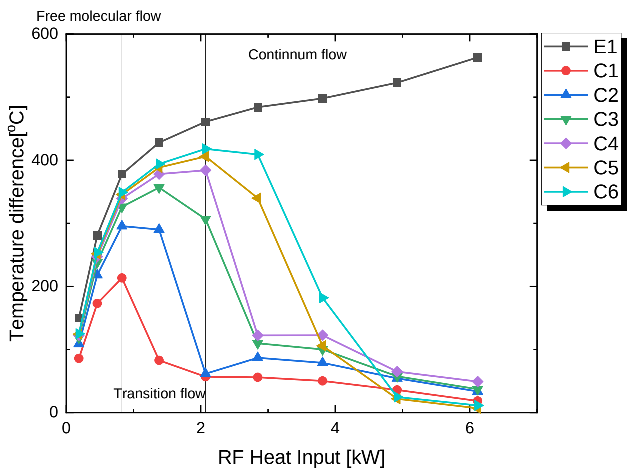


Fig. 6. Temperature behavior from startup to steady state of vertical condition

4. Conclusions

In this paper, initial behavior and steady-state experiments of an overcharged sodium heat pipe were conducted. The experimental results showed the initial behavior and isothermal performance of the sodium heat pipe. In the case of initial behavior, the tendency to enter the continuum flow from the frozen state through the viscous limit is similar, but there are differences in the detailed phenomena according to the inclination angle: 1) Formation of a puddle at the end of the condenser due to partial entrainment in the horizontal state, 2) Liquid Boiling of geysers caused by pool formation in the evaporator in the vertical state

This difference is understood as the location of liquid pool formation due to the fluid circulation by gravity and capillary action and the sufficient filling amount of the working fluid.

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REFERENCES

[1] M. M. Swartz, W. A. Byers, J. Lojek and R. Bluent, Westinghouse eVinci™ Heat Pipe Micro Reactor Technology Development, International Conference on Nuclear Engineering, Vol. 85246, p. V001T04A018, 2021.
[2] Oklopower, Part II: Final Safety Analysis Report, 2020.
A. Seoul, B. Deajeon, and C. Daegu, Article Title, Journal, Vol. 1, No. 1, pp. 1-10, 2002.
[3] A. Faghri, Heat pipe science and technology, 1995.
[4] H. Yang, C. Wang, D. Zhang, W. Tian, S. Qiu and H. Su, Parameter sensitivity study on startup characteristics of high temperature potassium heat pipe, Nuclear Engineering and Design, Vol. 392, p. 111754, 2022.
[5] Z. Tian, X. Liu, C. Wang, D. Zhang, W. Tian, S. Qiu and H. Su, Experimental investigation on the heat transfer performance of high temperature potassium heat pipe for nuclear reactor, Vol. 378, p. 111182, 2021.