Experimental Study of Sodium Heat Pipe by Calorimeter for H-MMR

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1. Introduction

H-MMR is designed to provide power to meet demand power through autonomous operation by combining nuclear, renewable and energy storage systems. To reduce the risk of LOCA, H-MMR is designed to remove reactor heat from the core by using heat pipe at atmospheric pressure. (Choi et al. 2020)

High temperature heat pipes were used for heat transfer in the solid core. The heat pipe can passively transfer heat from the core to the intermediate heat exchanger through a phase change in the internal working fluid. In addition, the heat pipe itself acts as a barrier to prevent the transfer of fission-generated material to the intermediate heat exchanger. The H-MMR configuration combines the core, safety system, power generation system and energy storage system. H-MMR can be able to produce energy more flexibly and efficiently through load following.

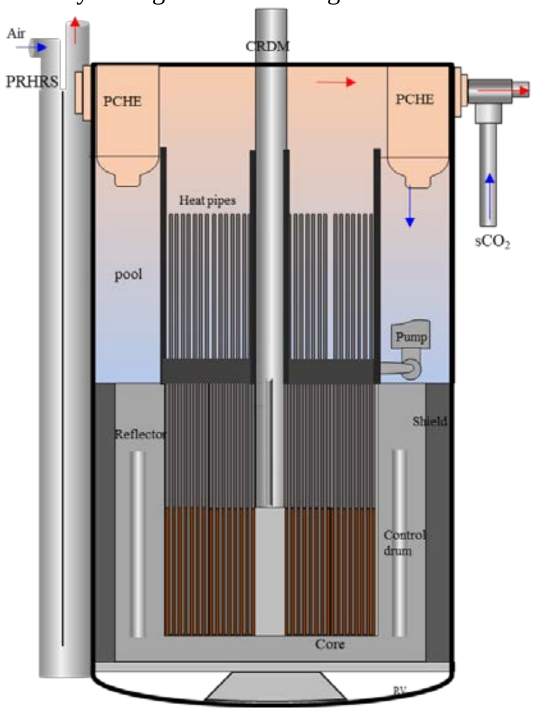

Fig.1. H-MMR reactor configuration and intermediate heat exchanger

The reactor core consists of 18 fuel assemblies and 990 heat pipes and nuclear fuel rods. The nuclear fuel is 99% N-15 uranium nitride (UN) and the cladding is ODS (Oxide Dispersion-Strengthened) operating between 600K and 1100K. As the diameter of the heat pipe and the fuel changed, the power cycle and fuel concentration changed through the core analysis. Economic analysis achieved a power cycle of about 56 years with 12.1% concentration of UN fuel at heat pipe diameter of 22 mm.

Table I: Parameter of H-MMR core

Parameters	Values
Reactor power	18 MWth
Fuel material	$U^{15}N$
Fuel enrichment (^{235}U)	12.10 w/o
N-15 enrichment	99.9 %
Cladding material	ODS
Gap material	Helium
Number of fuel assemblies	18
Number of fuel rod	990
Active core equivalent radius / height	61.46 cm / 120 cm
Whole core equivalent radius / height	99 cm / 280 cm
Burnup	37 GWD/T
Cycle	~56 years

2. Design of heat pipe for H-MMR

Heat pipes have been optimized in consideration of the working fluid, temperature, and internal structure. Compared to thermosiphons and conventional wick heat pipes, annular gap wick heat pipes are used in the design due to their superior operating performance. Sodium heat pipes perform far better than potassium at high temperatures, but potassium heat pipes are more suitable for the operating range of H-MMR.

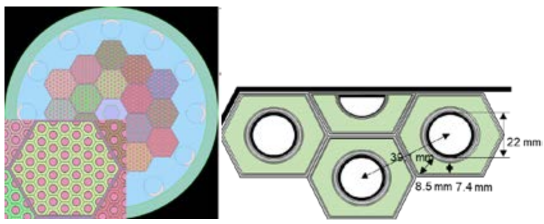

Fig.2. Hexa-annular fuel assembly with heat pipe

In order to determine the diameter of the heat pipe optimized for H-MMR, core analysis was performed according to the heat pipe diameter. The wick parameters (mesh size, wick and annulus thickness) were changed as shown in Table II to obtain optimal values for maximizing the heat pipe limit.

Table II: Parameter of heat pipe for H-MMR

Parameter	Values
Working fluid	Potassium (K)
Pipe material	SS316
Operating temperature	680 ~ 690 ^oC
Pipe outer diameter	22 mm
Length of evaporator: adiabatic: condenser	1.2 m: 1.2 m: 1.2 m
Wall: Annulus: Wick thickness	0.5 mm: 0.8 mm: 0.5 mm
Wick	400 mesh stainless steel wrapped screen wick
Minimum heat transfer limitation	31.4 kW

3. Experiment of heat pipe

When a duct is needed in the solid core of H-MMR, a semicircular (D shape) heat pipe was used. However, the experimental data of the D shape heat pipe with the annular liquid gap was insufficient.

The D shape heat pipe has been used in several special situations like wings and tails of airplanes and jets in high temperature conditions. D shape heat pipes are also used to cool hot surfaces such as radiators from satellites or space launch vehicles. Glass et al. (1997) conducted an experiment by fabricating a D-shaped high-temperature heat pipe used at the leading edge. Hong et al. (2020) tested a sodium filled horizontal alkali-metal heat pipe from a frozen state.

3.1. Experimental purpose

The outline of the experiment is scale-down experiment of the heat pipe used for H-MMR. We want to check whether it works normally in transient situations. In circular and semi-circle experiments, the results of heat pipe performance, code analysis, and temperature are compared and verified.

As shown in the test matrix below, the heat transfer and the performance of the heat pipe were compared according to the shape, diameter, type, orientation, and calorimeter. After the normal operation test is completed, operation limit test was performed to compare and verify the operation limit. In the case of circular heat pipes, it is compared with the existing equations, and in the case of D-shaped, a new correlation equation need to be developed.

Table III: Test matrix of heat pipe experiment

Test matrix	
Shape	Circle, D shape
Diameter	½, 5/8 , ¾ inch
Type	Thermosiphon, Annular gap
Orientation	Vertical, Horizontal etc.
Calorimeter	With, Without

3.2. Experimental apparatus

The heat pipe manufacturing process is as follows. A 200 mesh SS screen mesh core structure was wound on a copper rod. A 0.5mm SS316L wire was spot-welded to the wound wick structure to be bonded. Heat treatment for oxidation was performed at 450 ^oC for 2 hours. The wick was cleaned of contaminants with acid for 1 hour at 200 ^oC. By removing the copper rod inside, an annular wick structure was obtained. The wick structure was inserted into an SS pipe. The bottom and top caps were welded. A pressure leak test was performed to confirm that there was no air leak up to 6.2 bar. Finally, sodium was inserted into the pipe under vacuum after degassing. The heat pipe information of experiment is shown in Table IV.

Fig.3. Fabrication process of heat pipe and wick structure

Table IV: Parameter of experimental heat pipe

Experiment	Value
Working fluid	Sodium
Length of evap.: adia.: cond.	300 : 300 : 300 mm
Length of cap	5 mm
Wall thickness	1.24 mm
Wick	200 mesh SS wrapped screen
Wick thickness	7 layer, 0.5 mm
Annulus thickness	0.5 mm

The following is a picture of the experimental setup. RF induction heater transfers heat at the evaporator and the calorimeter cool the heat pipe at condenser. The variables to be checked through the experiment are the heat pipe wall temperature, the power and flow rate of the RF heater, the water flow rate of the calorimeter, and the inlet and outlet temperature.

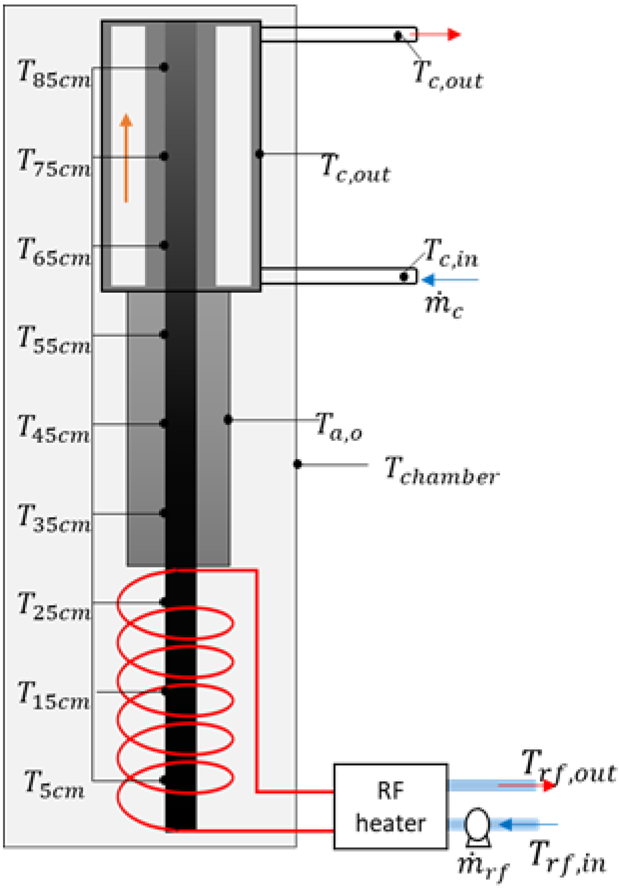

Fig.4. Heat pipe experimental apparatus

4. Results

The experimental apparatus was set up according to the above conditions. In the figure on the left, a semicircular heat pipe was heated horizontally without a calorimeter. In the picture on the right, a circular heat pipe was heated vertically and the heat was removed with a calorimeter. The experiment was carried out inside the chamber. After the experiment, the energy transferred through the heat pipe was calculated through the energy balance equation.

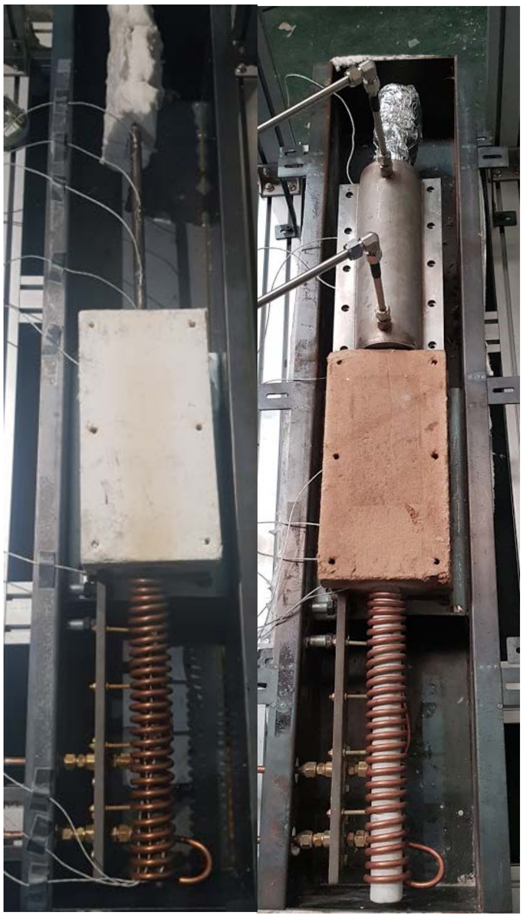

Fig.5. Heat pipe experimental setup: (left) without calorimeter, (right) with calorimeter

Fig. 6 is an experiment in which a semicircular heat pipe is heated horizontally without a calorimeter. At 15, 45, and 75cm, a TC was also installed on the flat part to check the temperature difference, and the temperature was measured while gradually increasing the output. In the experiment without a calorimeter, the surface temperature of the heat pipe was measured relatively high. The reason is that sufficient cooling was not achieved because the cooling was radiation and free convection. It was confirmed that the temperature of the adiabatic, the internal fluid temperature, increased to more than 800 ºC. The temperature difference between the evaporator and the condenser naturally occurred. The evaporator overheated because heat input is higher than the amount of heat removal.

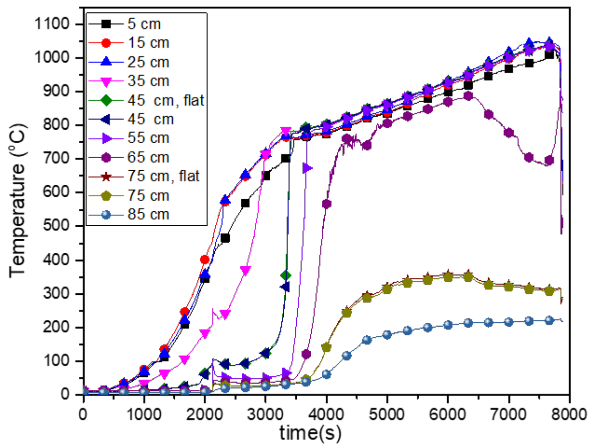

Fig.6. Temperature result of heat pipe (semicircle, horizontal, without calorimeter)

Fig. 7 is an experiment of heating a circular heat pipe with a calorimeter at 45^o angle. After about 1 hour, temperature at 5cm was about 700 ^{o}C, and the other evaporator and adiabatic temperatures were about 500 ^{o}C. After additional heating, the temperature difference between the evaporator and the adiabatic was about 50 ^{o}C apart. At some point, the evaporator and adiabatic temperature rapidly increased by more than 200 ^{o}C at the same time, and the RF heater power was cut off.

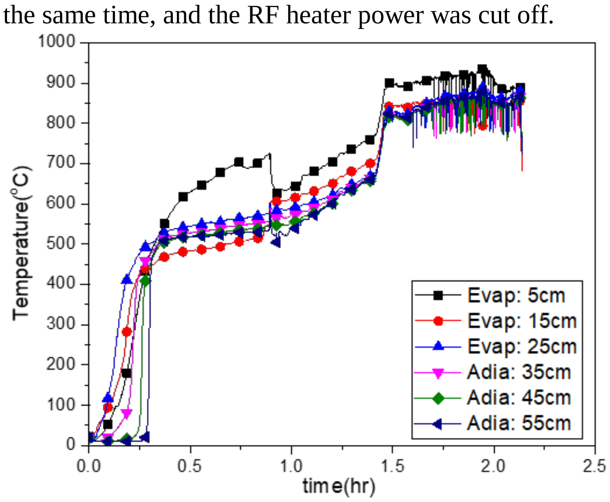

Fig.7. Temperature result of heat pipe (circle, 45^O, with calorimeter)

Figure 8 shows the amount of heat removed through the calorimeter in the circular heat pipe experiment as adiabatic temperature. It can be seen that the amount of heat removal from 500 ^{o}C increases along the sonic limit, and the temperature rises sharply at about 600 ^{o}C. Analysis on the characteristics of the water calorimeter is in progress.

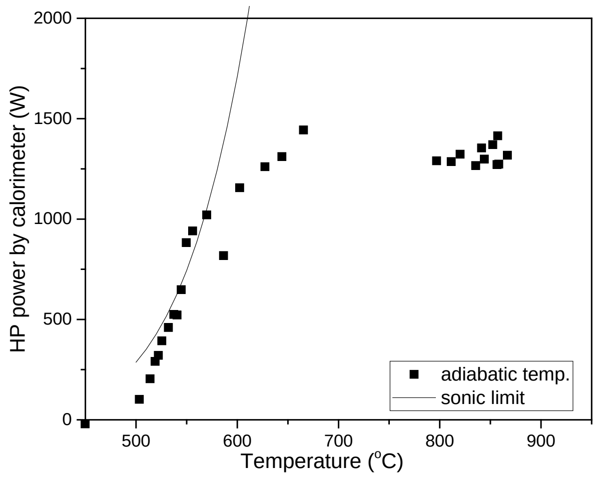

Fig.8. HP Heat transfer performance by calorimeter (circle, vertical, with calorimeter)

4. Conclusions

Heat pipe experiments were conducted on various conditions. Heat transport performance was measured with calorimeter and energy balance equation. Calorimeter effect was checked by temperature results and limitation curve. In Future works, heat pipe experiments will be conducted on different diameter and orientation conditions. Performance comparison with experiments and capillary limitation calculation will be conducted.

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REFERENCES

[1] Y. J. Choi et al., “Conceptual design of reactor system for hybrid micro modular reactor (H-MMR) using potassium heat pipe,” Nuclear Engineering and Design, vol. 370, 2020.

[2] D. E. Glass, C. J. Camarda, J. Tom Sena, and M. A. Merrigan, “Fabrication and testing of heat pipes for a heat-pipe-cooled leading edge,” National Heat Transfer Conference, 1997.

[3] S. D. Hong and C. S. Kim, “Startup Characteristic of a Horizontal Alkali-Metal Heat Pipe from a Frozen State,” Transactions of the Korean Nuclear Society, 2020.