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Design and analysis of safety system using heat pipe of hybrid micro modular reactor (H-MMR)

Young Jae Choi [a*], Seongmin Lee [a], Yong Hoon Jeong [a*]
[a] *Department of Nuclear and Quantum Eng., Korea Advanced Institute of Science and Technology,*
291 Daehak-ro, Yuseong-gu, Daejeon, 34141, Republic of Korea
[*]Corresponding author: jeongyh@kaist.ac.kr

1. Introduction

MMR (Micro-Modular Reactor) is a 36.2MWth supercritical CO_2 cooled Brayton cycle developed by KAIST, designed for 20 years life and weight of 155 tons, which can be transported by trailer. (Kim et al. 2007) H-MMR is designed to supply power to meet demand through autonomous operations for a long period of 20 years by combining nuclear, renewable and energy storage systems as shown in Figure 1. In the existing MMR, since supercritical CO_2 directly removes heat to the core and flows into the secondary system to generate power, the pressure of the entire system is about 20 MPa, which makes a risk of LOCA. In order to reduce the risk of LOCA, the H-MMR was designed to operate at atmospheric pressure and reactor design to sufficiently remove the heat from the core. The concept of a high-temperature heat pipe was used for heat transfer to the core. The heat pipe can transfer the heat of the core to the intermediate heat exchanger passively through a phase change of the internal working fluid. In addition, the heat pipe itself serves as an interface to prevent the transfer of fission-producing material to the intermediate heat exchanger. H-MMR configuration is shown in Figure 1 by combining the system of the core, safety system, power cycle, and energy storage system. H-MMR was able to produce energy more flexibly and efficiently through load following.

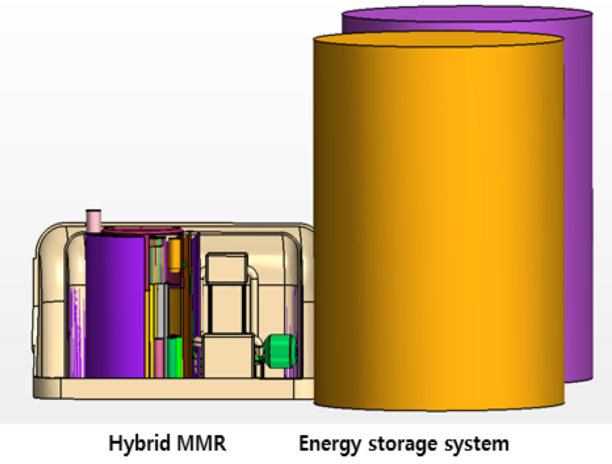

Fig.1. Conceptual view of hybrid micro modular reactor (H-MMR)

High temperature heat pipe using liquid metal as working fluid have been researched to nuclear system. Greenspan et al. (2008) assessed the feasibility of designing a safety system to cool solid cores by integrating liquid metal heat pipes into ENHS (Encapsulated Nuclear Heat Source) reactors. HP-ENHS provides high passive safety and transportability with natural circulation cooling and an operating period of 20 years. The heat pipe uses sodium, the working fluid temperature is 1300 K, and an average of 8 kW per heat pipe is eliminated. Sterbentz et al. (2017) proposed a 5MWt Special Purpose Reactor (SPR). A small fast reactor with a heat pipe cooling system was developed in INL. UO_2 is used as fuel and the working fluid of the heat pipe is potassium (K). Preliminary studies using high temperature heat pipes have been studied with small modular reactors with solid cores. Typical working fluids are potassium and sodium at sub-atmospheric pressure. The heat from the solid core is removed by the heat pipe without the coolant flow. Westinghouse is developing innovative eVinch micro reactors as next-generation small module nuclear reactors, which have a solid stainless steel monolith with fuel and heat pipe. Reactor system can eliminate conventional accidents like LOCA and SBO because it operates at low pressure and does not use primary coolant.

2. Design of heat pipe safety system for H-MMR

There are many advantages to applying a heat pipe to a reactor. The simplicity and modularity of the system for many single heat removal components enables innovative and flexible design. In the event of an accident, redundancy is guaranteed with a single point failure of the heat pipe. LOCA accidents can be prevented in advance by removing the primary coolant and coolant pump.

2.1 Design of reactor core

The fuel assembly of the H-MMR core is designed as a solid core with a heat pipe inserted without a coolant. As shown in Figure 2, the solid core was designed with a hexagonal annular nuclear fuel, and there was cladding inside and outside the nuclear fuel, and a heat pipe was inserted in the middle. The trapezoidal shape generated by the fuel assembly duct used a semicircular heat pipe. Since the output of the total H-MMR is 18 MWth and there are 18 fuel assemblies, 1 MW of heat per nuclear fuel assembly must be removed. Therefore, the heat of the inner 43 heat pipes should be 20.4 kW, and the semi-circle 12 heat pipes should be 10.2 kW. The semicircular heat pipe will be evaluated for performance through additional experiments and analysis.

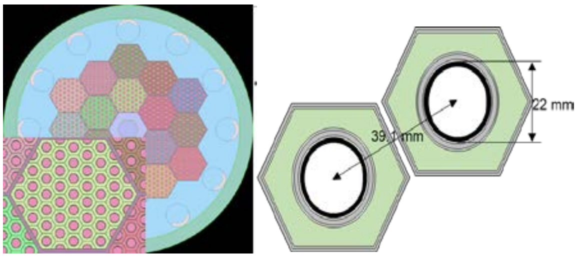

Fig.2. Hexa-annular fuel assembly with heat pipe inserted

Figure 3 shows the H-MMR primary reactor vessel of 5 m height. The heat of the core is transferred to the upper intermediate heat exchanger pool (IHXP) through the heat pipe, and finally to the sCO2 power cycle through the printed circuit heat exchanger (PCHE). The IHX pool has a hot pool at the top and a cold pool at the bottom, and there are 2 pumps and 4 PCHEs. The advantage of this design is that the heat pipe can transfer the core to the core without coolant, and the operating pressure is also reduced to the atmospheric pressure level to prevent serious accidents such as LOCA.

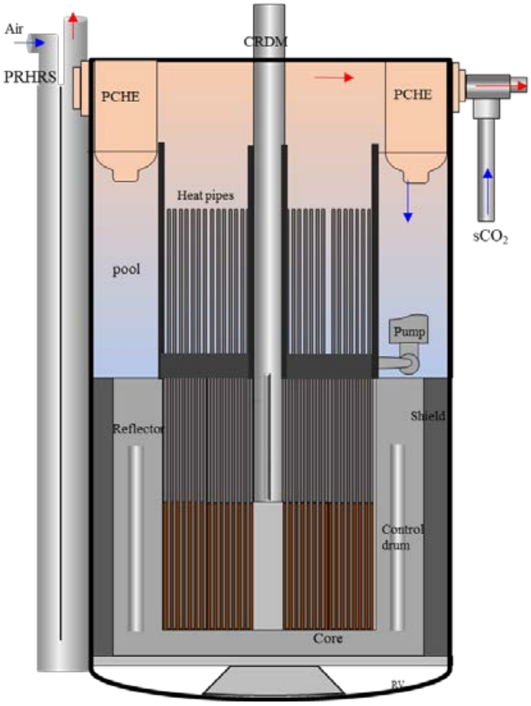

Fig.3. H-MMR reactor configuration and intermediate heat exchanger

CRDM control rod is located in the center of the core, and 12 control rods are located on the outer wall of the core. The reactor core consists of 18 fuel assemblies and a total of 990 heat pipes and nuclear fuel rods. The nuclear fuel is 99% N-15 uranium nitride (UN), which is more chemically stable and easier to manufacture than UC. The cladding used ODS (Oxide Dispersion-Strengthened), which operates between 600K and 1100K. As the diameter of the heat pipe and the temperature of the fuel changed, the output cycle and fuel concentration changed through the core analysis. Through economic analysis, the output cycle of about 52 years was achieved with UN fuel having a concentration of 12.1% when the heat pipe diameter was 22 mm. Table 1 shows the details of the design.

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	~52 years

2.2 Design of heat pipe

Heat pipe is a passive heat transport system with high heat transfer performance using fluid phase change. For the heat pipe suitable for H-MMR, it was optimized by considering the working fluid, temperature, and internal structure. An annular gap wick heat pipe was used to improve the internal capillary limitation by comparing the performance among thermosiphon and conventional wick heat pipe.

Figure 5 compares the operating limits of the heat pipe diameter, operating temperature and working fluid (sodium, potassium). The sodium heat pipe has much better power limitation performance than potassium at high temperature, but potassium heat pipe showed better results in the operating range of H-MMR.

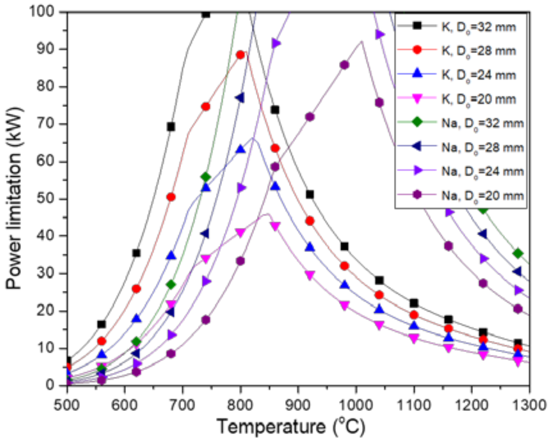

Fig.5. Power limitation with working fluid of annular wicked heat pipe

In order to determine the diameter of the heat pipe optimized for H-MMR, core analysis according to the diameter of the heat pipe was performed. The figure 4 is the result of the multiplication factor. As the diameter of the heat pipe decreases, the EFPY increases, and the operating limitation of the heat pipe decreases. Therefore, the optimal diameter (22mm) was selected for the safety and economy. The detailed heat pipe information is shown in Table 2. By changing wick parameters (mesh size, wick and annulus thickness), optimum value was obtained to maximize the heat pipe limitation.

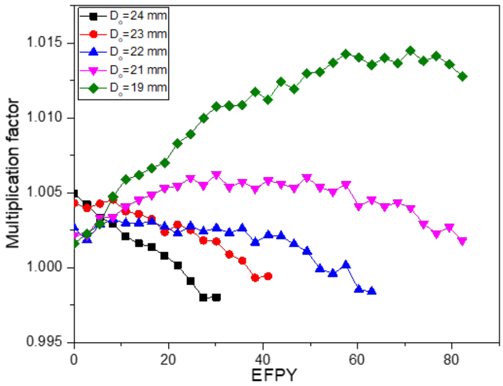

Fig.4. Reactor multiplication factor by changing heat pipe diameter

Table II: Parameter of heat pipe for H-MMR

Parameter	Value
Working fluid	Potassium (K)
Pipe material	SS 316
Operating temperature	680 ~ 690 °C
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
Number of heat pipe	990
Minimum heat transfer limitation	31.4 kW

3. Analysis of heat pipe safety system for H-MMR

3.1 Heat transfer analysis of heat pipe with solid core

Figure 6 is a two-dimensional numerical modeling of the heat transfer of the H-MMR heat pipe core cooling system using the implicit Finite Differential Method (FDM). The overall temperature distribution during normal operation was calculated using the following equations.

$$\left(\sum_k \frac{L_k}{A_k}\right)\frac{d\dot{m}}{dt} = \Delta p_{pump} - \Delta p_{friction} - \Delta p_{form} + \Delta p_{buoyancy}$$

$$h_i^p = h_i^{p+1} + \frac{G\Delta t}{\rho^p \Delta l}\left(h_i^{n+1} - h_{i-1}^{n+1}\right) - \frac{A\Delta t}{\rho A_F \Delta l} q''$$

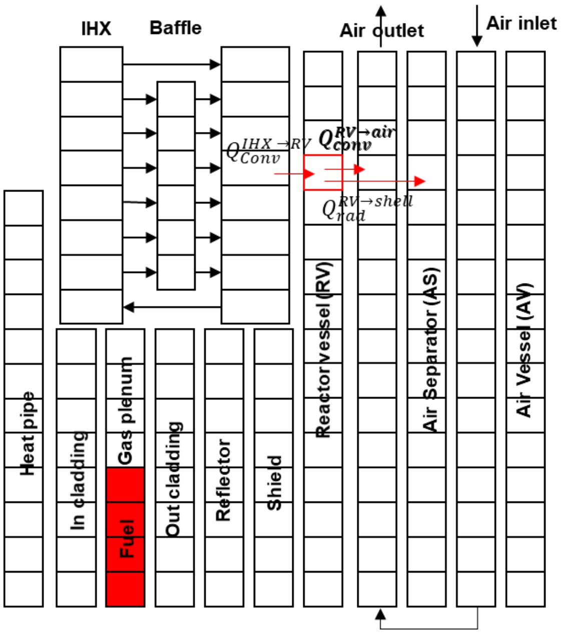

Fig.6. H-MMR nodalization with RVACS

Figure 7 shows the temperature profiles analyzed for finite difference modeling, As a result of calculation, the average temperature of fuel, inner-cladding and heat pipe was 738 °C, 704 °C and 688 °C.

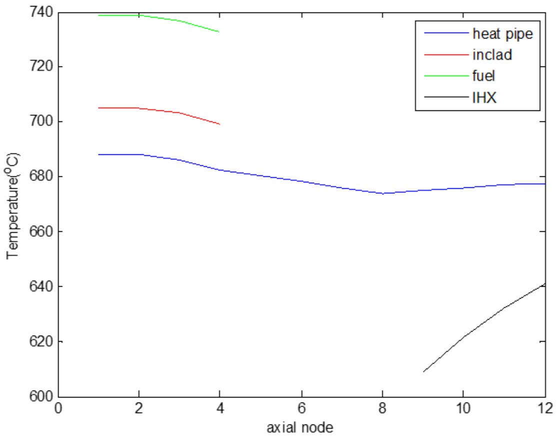

Fig.7. Average axial temperature profile along heat pipe

3.2 Reactor Vessel Auxiliary Cooling system (RVACS)

The passive residual heat removal system is designed to remove residual heat through the outer wall of the reactor vessel using external air in the event of an accident. Residual heat removal performance was designed to have 1~2% residual heat removal performance of normal output, and the difference between high residual heat generation amount and residual heat removal amount in the early stage of accident was designed to accumulate in the safety system. The IHX sodium pool transfers heat through circulation passively by buoyancy.

At 1000 s, the performance of RVACS was compared according to the air path thickness. When the flow path spacing was 6 cm, the heat transfer was maximum at 225 kW. Heat transfer at RVACS was analyzed and the total temperature is as follows. Air velocity is about 3m/s, outlet temperature is about 225 °C.

Table III: Result of RVACS analysis at 1000s

RVACS at 1000 s	
Working fluid	Air
Inlet Temp.	50 °C
Channel	U shape
RV- AS – AV thickness	5 - 2 - 2 cm
Air flow path width (S)	6 cm
Mass flow rate	1.2 kg/s
Velocity	2.8~3.8 m/s
Reynolds number	15,000~18,000
Heat transfer coefficient	5~6 W/m^{2}K
Heat transport	225 kW

As a result of the transient analysis, temperature and heat transfer graphs were obtained in Figure 8. Air flow remove 225 kW at 1000s. Until 100,000s, heat transfer has 4 steps. After reactor shutdown, temperature redistribution occurs in step 2. Subsequently, in step 3, the decay heat is greater than the heat removal amount, and heat is accumulated in the system. Finally, when the heat removal amount is higher than the decay, the system temperature drops. After performing RVACS implicit transient analysis, RVACS was analyzed to keep the temperature of the system within the design limit.

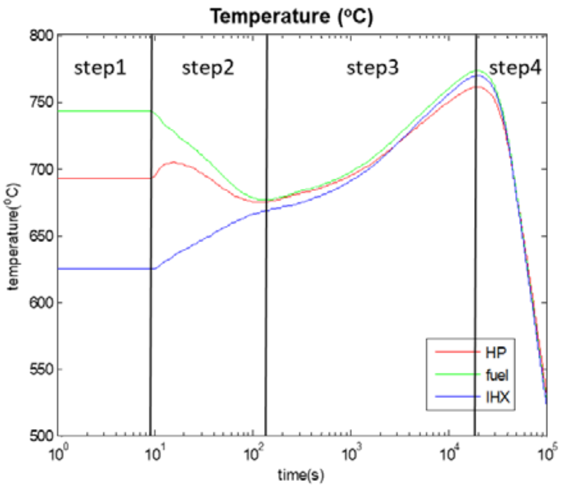

Fig.8. Transient temperature of H-MMR core after shutdown

3. Conclusions

The design of a hybrid micro modular reactor (H-MMR) combined with renewable energy and energy storage system (ESS) was introduced. It is designed to remove the heat of the core by using a solid core using a heat pipe and a pool type intermediate heat exchanger. The detailed design and performance of the potassium heat pipe were optimized, and the core heat transfer performance was evaluated. In the event of an accident, the residual heat removal system of H-MMR was intended to remove residual heat by cooling the outer wall of the reactor vessel. It was confirmed that residual heat was removed through the lumped implicit transient analysis.

ACKNOWLEDGMENTS

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REFERENCES

[1] S. G. Kim et al., “Conceptual system design of a supercritical CO_2 cooled Micro modular reactor,” Int. Top. Meet. High Temp. React. Technol. HTR 2016, vol. 2, pp. 613–620, 2016.
[2] E. Greenspan et al., “Innovations in the ENHS reactor design and fuel cycle,” Prog. Nucl. Energy, vol. 50, no. 2–6, pp. 129–139, 2008.
[3] J. E. Werner et al., “Preliminary Assessment of Two Alternative Core Design Concepts for the Special Purpose Reactor,” November, 2017.