Analysis of heat pipe safety system of Hybrid Micro Modular Reactor (H-MMR)

Young Jae Choi, Jangsik Moon, Yong Hoon Jeong*
Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology,
291, Daehak-ro, Yuseong-gu, Daejeon, 305-701, Republic of Korea
*Corresponding author: jeongyh@kaist.ac.kr

1. Introduction

Globally, small-sized module nuclear power plants are highly interested and demanded in countries where distributed power sources are needed and countries with small power grid capacity. Micro modular reactor (MMR) is a fast reactor of 36.2 MWth and supercritical CO_2-cooled Brayton cycle developed in KAIST. The purpose of this study is to develop a hybrid micro modular reactor (H-MMR), which combines renewable energy like solar energy and energy storage system (ESS) with MMR as shown in Figure 1. The hybrid MMR system can produce energy more flexibly and efficiently through autonomous load follow-up operation with ESS. To operate hybrid MMR, highly passive and active safety system are required for several accident scenarios. For the safe operation of H-MMR, the completely passive and reliable active safety system is required, and concept of heat pipe is applied.

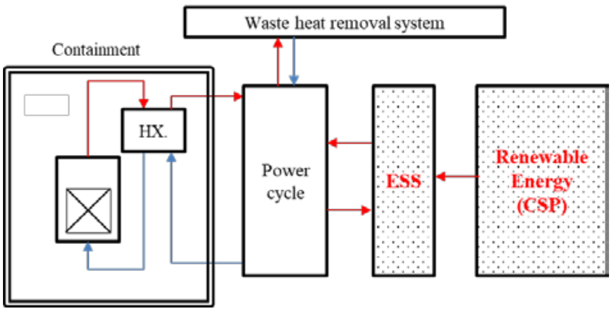

Fig. 1. Conceptual view of nuclear and renewable hybrid MMR

2. Design of heat pipe system

Heat pipe is a complete passive heat removal device with high heat transfer performance by phase change of fluid. The type of heat pipe is a capillary heat pipe driven by capillary force of the wick structure and thermosiphon driven by gravity. High temperature heat pipe that has good heat transfer performance is suitable for H-MMR.

There are several advantage of using heat pipe for nuclear reactor. The simplicity and modularity of system are increased by the many single heat removal components, resulting in innovative flexible design. The redundancy is also increased by single-point failure of heat pipe. Also, LOCA accident doesn't happen because the primary coolant and pump doesn't exist. Finally, passive thermal heat removal is possible during normal operation or accident situations.

In application of heat pipe to the H-MMR reactor, the operating limitation of heat pipe should be calculated and evaluated for safe utilization of heat pipe. In consideration of working fluid and temperature, figure of merit (FOM) is used to compare the relative performance of working fluids. FOM is shown in Figure 2. Cesium, potassium, sodium and lithium show good performance in high temperature.

In H-MMR, capillary-type heat pipe was used due to the high operating limitation. Sodium was used as the working fluid. The dimensions of heat pipe are shown in Table 1.

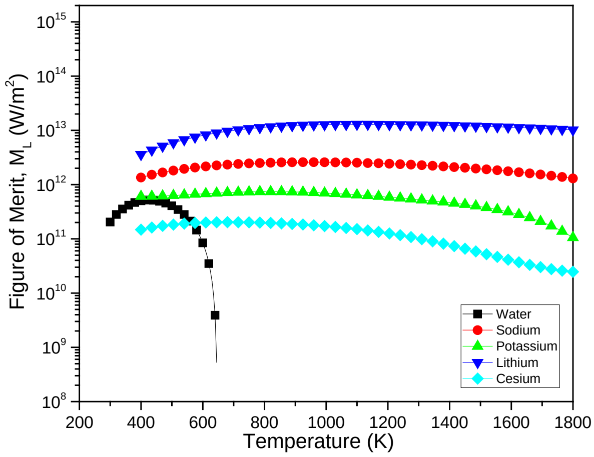

Fig. 2. Figure of merit (FOM) of heat pipe

Table 1. Dimension of heat pipe on H-MMR

Parameter	Value
Evaporator length	1.2 m
Adiabatic length	1.2 m
Condenser length	1 m
Outer diameter	20 mm
Wall thickness	0.5 mm
Annulus thickness	0.5 mm
Wick thickness	1.0 mm
Mesh	400 mesh
Wick wire diameter	0.025 mm
Porosity of wick	0.8

The heat transfer limits of a capillary heat pipe are viscous, sonic, entrainment, boiling, and capillary limitations. The heat transfer limits of thermosiphon and capillary wicked heat pipe were compared according to the structure of heat pipe. As a result, the heat pipe of the annular gap wick structure shown in Fig. 3 showed higher heat transfer limit ability. Fig. 4 is a graph showing the operating limits of the heat pipe in the annular structure according to the internal temperature of the heat pipe. When the safety margin is 3, the removable power per 20mm diameter heat pipe is about 17kW at 1bar.

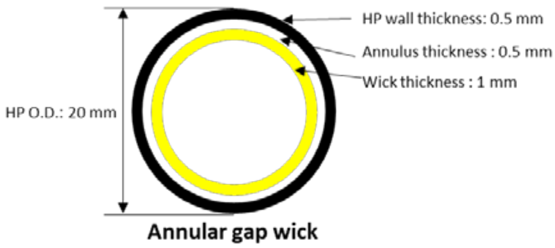

Fig. 3. Annular wick structure of capillary wicked heat pipe

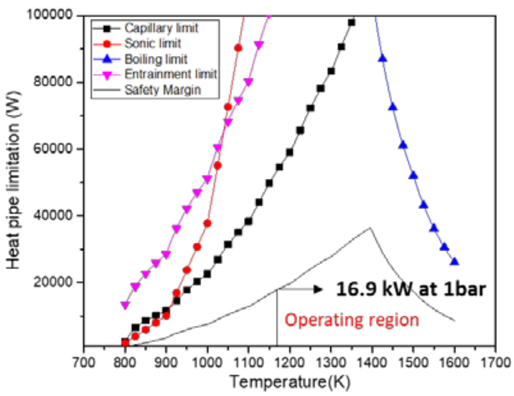

Fig. 4. Operating limits of the heat pipe in the annular gap wick

3. Design of heat pipe safety system on H-MMR

Application of heat pipe to nuclear reactor can cause several advantages for design and safety. The main purpose is heat removal during normal operation and accident situations. Because the design doesn't need primary coolant and pump, passively heat removal is possible and LOCA accident would not occur. Figure 5 show the schematic diagram of H-MMR which contains the primary side of the reactor core, intermediate loop and the supercritical CO_2 Brayton power cycle. An intermediate heat exchanger (IHX) was designed to connect with the power cycle. Although the working fluid of sodium is first used, we will evaluate the various fluids and then find the optimum material.

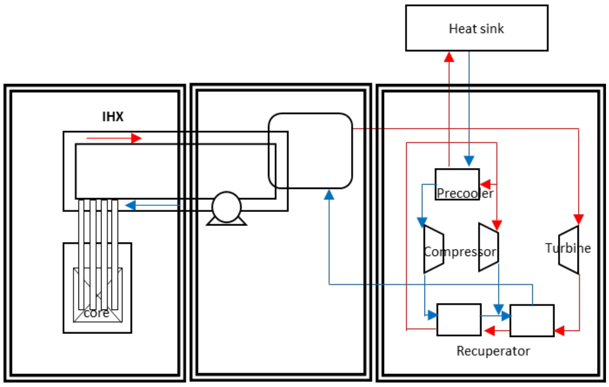

Fig. 5. Schematic diagram of H-MMR heat transport system

The fuel assembly of the H-MMR core was designed by replacing the fuel rod with a heat pipe as shown in Figure 6. The feasibility of cooling the solid core using heat pipe was evaluated in normal operation. The first core structure is a solid stainless steel in which the fuel and heat pipe are inserted and is designed to remove heat through thermal conduction through solid steel. The second core structure is a form in which black parts like briquettes are all fuel and heat pipes can be inserted. The third design is a sodium pool with heat transfer through sodium. The informations of fuel assembly of H-MMR are shown in Table 2.

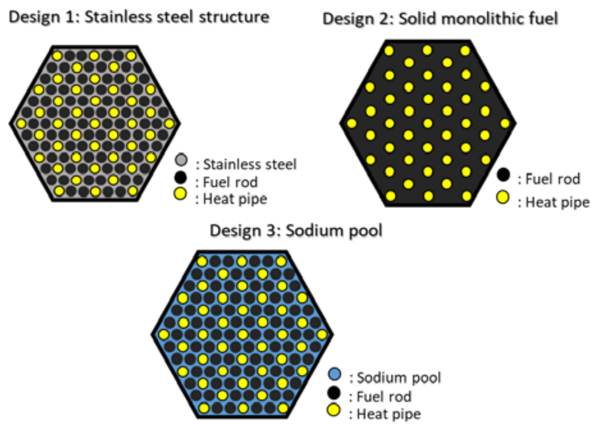

Fig. 6. Fuel assembly design of H-MMR core using heat pipe

Table 2. Fuel assembly of H-MMR core

Parameter	Value
Reactor thermal power	12 MWth
Number of Fuel assembly	18
Number of fuel rod/Fuel assembly	84
Number of HPs/Fuel assembly	43
Fuel material	UN
Fuel rod outer diameter	20 mm
Cladding thickness	0.5 mm

Gap thickness (helium)	0.1 mm
Cladding material	ODS
Pitch to diameter (P/D)	1.13

Figure 7 is the minimum unit of the fuel assembly 'design1'. Sub-channel analysis was performed to evaluate the feasibility of heat removal from fuel rod to heat pipe. Boundary conditions were the outer wall temperature of the heat pipe and the heat source of the fuel part. Figure 8 shows the finite element method (FEM) results using MATLAB. The highest temperature was in the center of the fuel and at 1214 K. Other 'designs2' and 'design3' were also performed thermal analysis. The maximum fuel temperature was 1242 K for 'design2' and 1197 K for design 3.

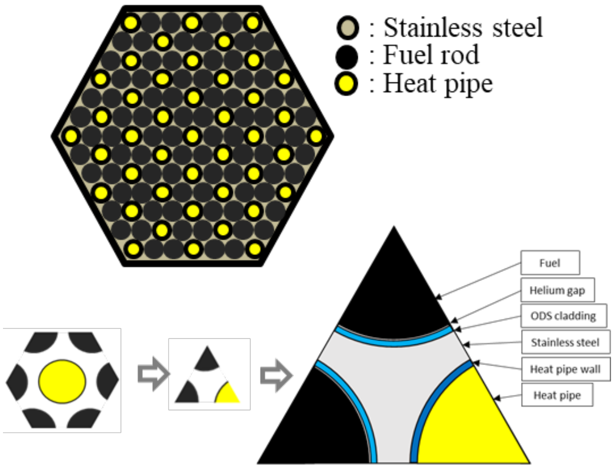

Fig. 7. Minimum cut of 'design 1' sub-channel of H-MMR

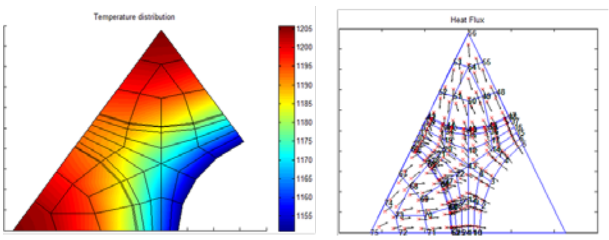

Fig. 8. FEM sub-channel analysis of 'design 1' of H-MMR

Figure 9 show the 1D thermal resistance, which represents the heat removal path of the core through the heat pipe. The heat generated from the active core is transferred to the evaporator part of the heat pipe through the stainless steel medium. The heat transfer equations of the cylindrical structure and the liquid, wick, evaporation and condensation parts finally lead to the convective heat transfer of the condenser. The inlet temperature and mass flow rate of the intermediate heat exchanger (IHX) were set as input values. Accordingly, the outlet temperature of the IHX, the overall temperature distribution of the heat pipe, and the average temperature of the core was calculated. If the inlet mass flow rate is 100 kg/s and the inlet temperature is 700 °C, the outlet temperature of the IHX will be 795 °C and the pressure drop will be 1.4 kPa. The temperature of the active fuel is 873 °C as shown in Table 3 and 4.

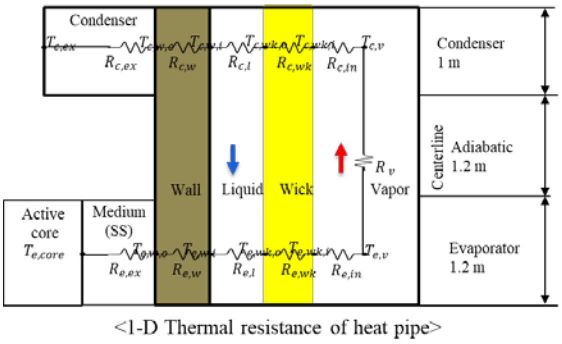

Fig. 9. Conceptual view of nuclear and renewable hybrid MMR

Table 3. Results of intermediate heat exchanger (IHX) analysis

Parameter	**Value**
Core power	12 MWth
IHX mass flow rate	100 kg/s
IHX inlet temp.	700 °C
IHX outlet temp.	795 °C
IHX temp. increment	95 °C

Table 4. Results of heat pipe thermal resistance analysis

Parameter	**Value**
Fuel temp.	873 °C
Evap. wall temp.	854 °C
Heat pipe vapor temp.	844 °C
Condenser wall temp.	826 °C
IHX temp.	748 °C

4. Conclusion

The hybrid MMR utilizes an innovative passive heat pipe to design coolant-free core cooling system during normal operation. The characteristics of heat pipe applicable to this nuclear power plant, temperature - dependent operating limits and heat transfer performance were evaluated and optimized. An annular wick-structured capillary heat pipe showed the best performance. In the first year, when evaluating the possibility of core cooling as a passive safety system of a heat pipe, a bar type structure with a heat conduction structure was evaluated as appropriate. In the second year, the heat pipe core cooling system was designed during normal operation and safety analysis was performed using FEM for three solid cores. In addition, the possibility of cooling the core cooling system using the total heat resistance of the heat pipe system was evaluated during normal operation and the intermediate heat exchange system (IHX) was designed.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korean government(Ministry of Science and ICT) (No. NRF-2017M2B2B1071970)

REFERENCES

[1] Faghri A. Heat Pipes: Review, Opportunities and Challenges. Front Heat Pipes. 2014.

[2] Faghri A. Review and Advances in Heat Pipe Science and Technology. J Heat Transfer. 2012.

[3] El-Genk MS, Tournier J-MP. Uses of Liquid-Metal and Water Heat Pipes in Space Reactor Power Systems. Front Heat Pipes. 2011

[4] Manoj R, Kumar MC, Narasimharao R, Narasimha KR, Suresh PVS. Frontiers in Heat Pipes PERFORMANCE EVALUATION OF SODIUM HEAT PIPES THROUGH PARAMETRIC STUDIES. 2012.

[5] Kemme JE. Ultimate Heat-Pipe Performance. IEEE Trans Electron Devices. 1969.

[6] Kim KM, Jeong YS, Kim IG, Bang IC. Development of Passive In-Core Cooling System for Nuclear Safety Using Hybrid Heat Pipe. Nucl Technol. 2016.

[7] Jeong YS, Kim KM, Kim IG, Bang IC. Hybrid heat pipe based passive in-core cooling system for advanced nuclear power plant. Appl Therm Eng. 2015.

[8] Greenspan E, Hong SG, Lee KB, et al. Innovations in the ENHS reactor design and fuel cycle. Prog Nucl Energy. 2008.

[9] Werner JE, Hummel AJ, Kennedy JC, et al. Preliminary Assessment of Two Alternative Core Design Concepts for the Special Purpose Reactor. 2017.

[10] Greenspan E. Solid-Core Heat-Pipe Nuclear Battery Type Reactor. 2006.

[11] Wang C, Zhang D, Qiu S, Tian W, Wu Y, Su G. Study on the characteristics of the sodium heat pipe in passive residual heat removal system of molten salt reactor. Nucl Eng Des. 2013.

[12] Bragg-Sitton SM, Boardman R, Rabiti C, et al. Nuclear-Renewable Hybrid Energy Systems: 2016 Technology Development Program Plan. 2016.

[13] Singh, R, Mochizuki, M., 2011, “Heat Pipe Based Emergency Cooling System for Removing Decay Heat from Nuclear Power Reactor and Spent Fuel Pool”, Japan Association of Heat Pipe Meeting, Tokyo, Japan.

[14] Mochizuki, M., Singh, R., and Nguyen, T, 2014, “Heat Pipe Based Passive mergency Core Cooling System For Safe Shtudown of Nuclear Power Reactor”, Applied Thermal Engineering.