Design of passive residual heat removal system of hybrid micro modular reactor (H-MMR) using heat pipe

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 and medium sized reactors are growing in interest and demand, especially in areas where dispersed power sources are needed or in countries that lack water. Small-sized module nuclear power plants produce the entire system as a module, and when the power generation capacity increases, many units can be produced. Therefore, a supercritical CO_2 cycle has been proposed as a substitute for the existing steam cycle and next generation nuclear power generation system. A study on supercritical CO_2 cooled mirco modular reactor (MMR) has conducted in KAIST. The integrated supercritical CO_2 cooled small module reactor system achieved the following goals: 36MWth of heat output, 34% of power generation efficiency, 20 years of design life of core and components, and design of complete passive safety system and long life core concept.

In this study, we will develop a hybrid micro modular reactor (H-MMR), through the fusion of a micro modular reactor (MMR) with a renewable energy and energy storage system (ESS). Renewable energy can help to generate electricity using solar energy. In addition, the ESS system is used to store the remaining heat and to make complementary electricity production when needed. The concept of hybrid micro modular reactor (H-MMR) is shown in Fig. 1, in which the core and the power cycle are separated to form a double loop. Hybrid MMR is designed to design a 100% autonomous operation nuclear power plant capable of actively coping with renewable power generation and external power demand. For safety in reactor accident, we will design the passive residual heat removal system of hybrid MMR by applying the concept of heat pipe which can passively remove heat.

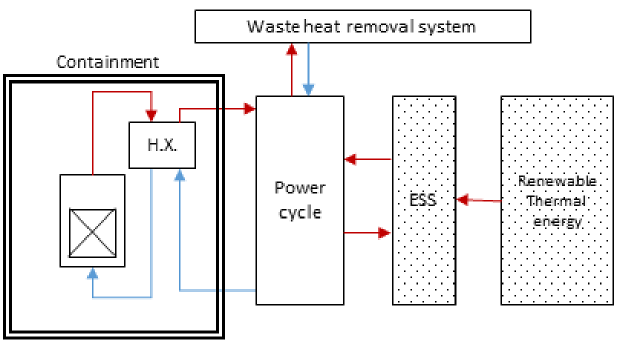

Fig. 1. Conceptual view of nuclear and renewable hybrid MMR power generation system

2. Design of heat pipe

Heat pipe is a complete passive heat removal device with high heat transfer performance using phase change of fluid in Fig. 2. The type of heat pipe is largely a capillary-type heat pipe using the capillary force of the wick structure and a gravity-type heat pipe driven by gravity, thermosyphon. High temperature heat pipe with good heat transfer performance is suitable for H-MMR. Sodium was used as the working fluid, and its melting point was 371 K (98°C) and its boiling point was 1151 K (878°C) at 1 atm.

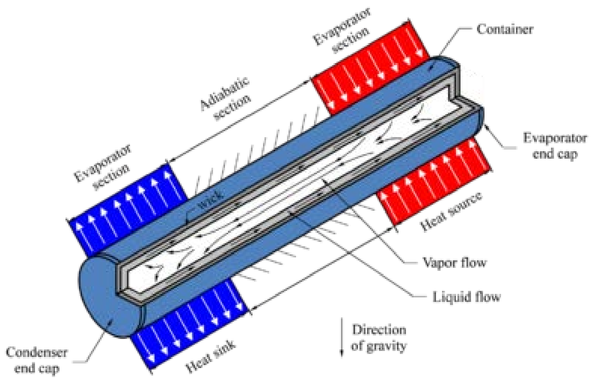

Fig. 2. Capillary-type heat pipe

The heat pipe to be applied to the hybrid MMR is designed to be 3.4 m in total length, 0.5 mm in pipe thickness, 1.2 m in evaporation part, 1.2 m in heat insulation part and 1 m in condensation part as shown in Table 1. The outer diameter of the heat pipe was 15 mm and the wick structure was a wrapped screen wick. The thickness of the wick was 1 mm and the diameter of the wick wire was 0.025 mm.

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
Heat pipe wall thickness	0.5 mm

Wick structure	Wrapped screen wick
Wick thickness	1.0 mm
Wick wire diameter	0.025 mm
Mesh number	400 in^{-1}
Porosity	0.78

The performance of heat pipe is affected by the working fluid, the structure of the wick, the size of the pipe, the internal fluid situation, and so there is a limit of the heat transfer amount. The heat transfer limits of a capillary heat pipe are viscous, sonic, entrainment, boiling, and capillary limitations. Gravity heat pipes, thermosiphon, determine the heat transfer performance due to the other four limits except capillary limit. 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 wick structure shown in Fig. 3 showed higher heat transfer limit ability. This is because the gap of the annular structure make the liquid frictional pressure drop small and the capillary limitation is calculated to be high. 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. The operating range is determined by the limit of sound velocity at low temperature and by capillary limit at high temperature.

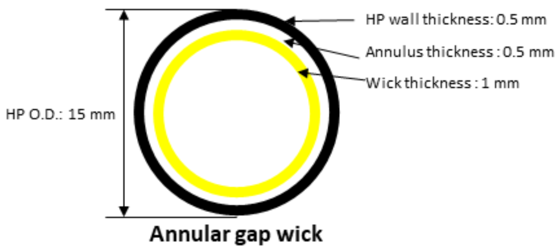

Fig. 3. Annular wick structure of capillary wicked heat pipe

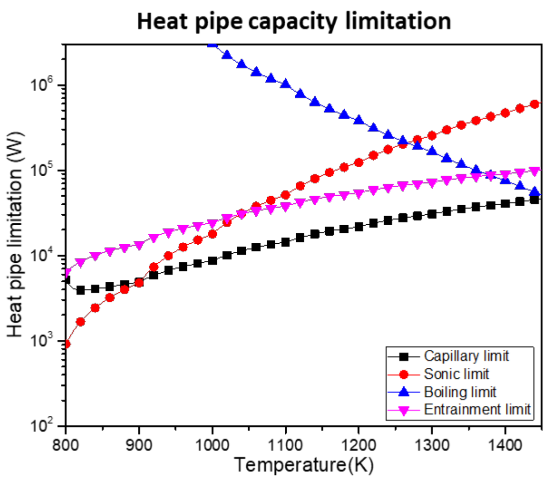

Fig. 4. Operating limits of the heat pipe in the annular gap wick

3. Design of passive residual heat removal system

The passive residual heat removal system shall be designed so that the pressure, temperature and cladding temperature in the reactor system at the time of the accident can be maintained within design limits. A key innovation in the passive residual heat removal system is the use of heat pipes to remove residual heat from the core. In the steady state, heat is transferred to the secondary side through supercritical carbon dioxide. In the case of design basis accident such as a coolant loss accident, heat is removed passively by using a heat pipe. When the reactor is shut down, the reactor core can be cooled stably by removing 430 kW of heat.

As shown in Fig. 5, a two-stage heat pipe cooling system was developed to remove decay heat. Two-stage heat pipe systems have two stage of heat pipes. Heat from the core is sent to the intermediate storage system through the primary heat pipes, and heat is sent through the secondary heat pipes to the external heat sink. The intermediate storage material is assumed to be liquid metal material. In addition, the fluid of the secondary heat pipe and the external heat sink uses water.

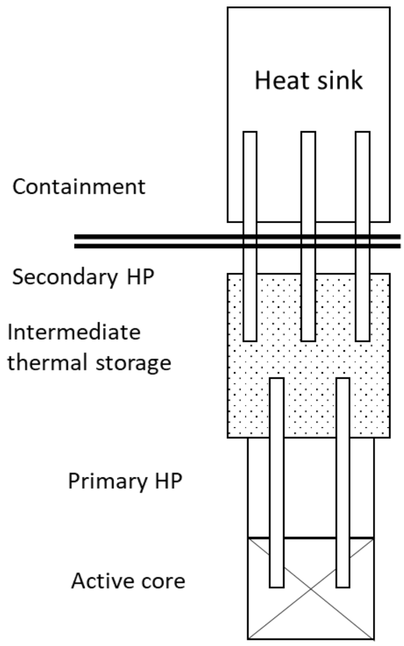

Fig. 5. Two step heat pipe system for H-MMR

The primary heat pipe can be designed as an annular structure and a rod shape as shown in Fig. 6 and Fig. 7. In the case of the annular structure, the heat pipe is inside the nuclear fuel, and it is necessary as many as the number of the fuel rod. At this time, the energy required to remove the residual heat per heat pipe is 0.19 kW, and heat pipe operation limit is calculated. As a result, heat can be removed under the condition of 1 atm. However, the annular structure is difficult to manufacture and has a disadvantage of requiring more than 2000 pipe. In addition, it is not a good design because the heat transfer ability of the heat pipe becomes small due to the thin diameter of 6 mm.

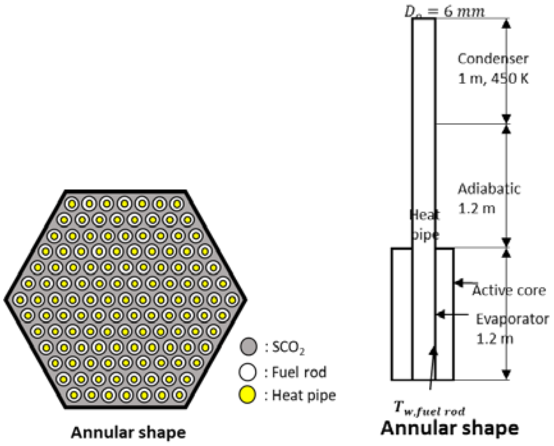

Fig. 6. Annular shape of primary heat pipe

In the case of the rod-shaped structure, the heat pipe is replaced with a fuel rod and designed to remove heat by one heat pipe per two fuel rods. At this time, the energy required to remove the residual heat per heat pipe is 0.6 kW. Figure 8 shows the heat transfer from the fuel rod to the heat pipe only for radiation (left) and for the case with heat conduction material (right). In the case of heat transfer through radiation only, the fuel rod temperature increased and eventually fail due to the high radiation thermal resistance, therefore the residual heat was not removed. Conduction heat transfer with a conduction structure can remove residual heat in Fig.8(right). The minimum contact area between heat pipes and fuel rods is needed to calculate to remove the decay heat without the fuel rod failure. Figure 9 show heat removal performance of rod shape-heat pipe with conduction structure. Pressure inside heat pipe is 0.05 bar and boiling temperature of sodium is about 900 K. The temperature of condenser is assumed as 450 K. If the temperature difference between core wall and condenser is about 800 K, heat removal is possible. However, the disadvantage of this structure is that the supercritical CO_2 pressure drop becomes large due to the heat conduction structure. By coupling with the core analysis, the size of the core need to increase due to the missing fuel rod.

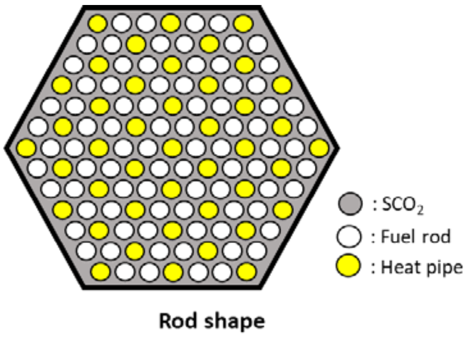

Fig. 7. Rod shape of primary heat pipe

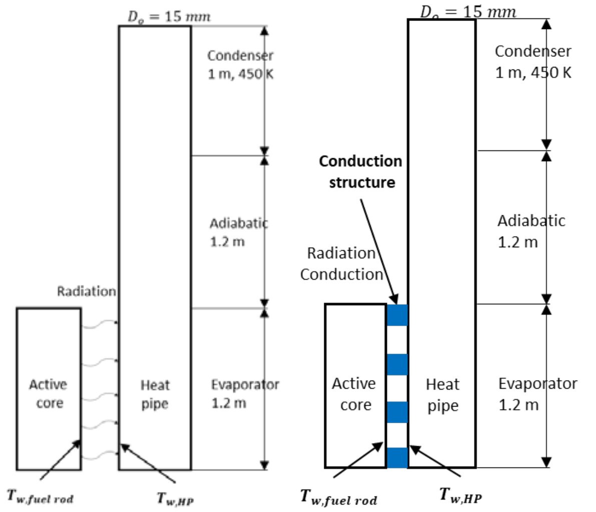

Fig. 8. Rod shape of primary heat pipe with no structure (left) and conduction structure (right)

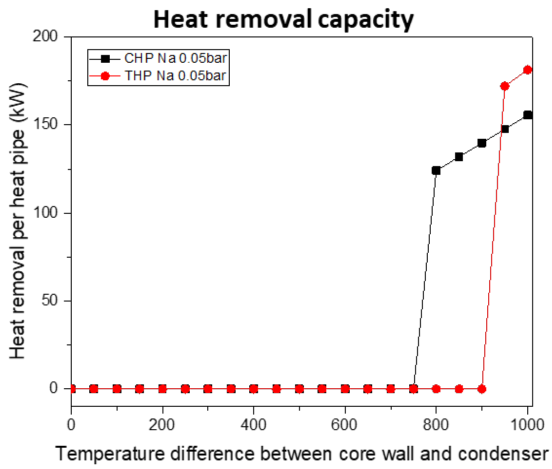

Fig. 9. Heat removal performance of rod shape-heat pipe with conduction structure

4. Conclusion

By evaluating heat transfer performance of various type heat pipe, we designed the heat pipe design suitable for hybrid MMR. The feasibility of a two-stage heat pipe system was evaluated by a passive residual heat removal system in case of an accident. Among the heat pipes of the annular and bar type structure, the design suitable for the hybrid MMR is evaluated as a bar type structure having a heat conduction structure. In addition, the possibility of steady-state heat pipe core cooling was additionally evaluated. The applicability to the existing core of two-stage heat pipe was evaluated and the modified core for 36 MW heat output was analyzed.

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] J. E. Werner *et al.*, “Preliminary Assessment of Two Alternative Core Design Concepts for the Special Purpose Reactor,” no. November, 2017.
[2] E. Greenspan, “Solid-Core Heat-Pipe Nuclear Battery Type Reactor,” no. 2, pp. 1–17, 2006.
[3] A. Faghri, “Review and Advances in Heat Pipe Science and Technology,” *J. Heat Transfer*, vol. 134, no. 12, p. 123001, 2012.
[4] K. M. Kim, Y. S. Jeong, I. G. Kim, and I. C. Bang, “Development of Passive In-Core Cooling System for Nuclear Safety Using Hybrid Heat Pipe,” *Nucl. Technol.*, vol. 196, no. 3, 2016.