Analysis for the Heat Pipes Failure in a Hybrid Micro Modular Reactor

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1. Introduction

The safety issues of nuclear power plants have received considerable attention after the Fukushima accident. The loss of coolant accident (LOCA) is regarded as one of the most serious conditions in which radioactive materials can be released outside the nuclear power plant. As one of the ways to improve safety, heat pipes can be applied to the reactor core. The heat from the reactor core is used to vaporize the working fluid inside the heat pipe. The vapor is condensed at the condensation region. Because of this principle, it is not necessary to pressurize the coolant to increase the boiling point or the heat capacity. Therefore, the reactor equipped with heat pipes is able to operate under the atmospheric pressure condition without using the primary coolant.

However, even though the use of heat pipes naturally avoids the potential risk of the standard LOCA accidents, severe conditions such as long-term irradiation and exposure to high temperatures may lead to heat pipe failure. In preparation for the heat pipe failure, it is necessary to evaluate how the heat pipe failure affects the temperature of the fuel and cladding. In this study, a safety evaluation was performed for the hybrid micro modular reactor (H-MMR) equipped with heat pipes, by estimating the temperature distribution and applied heat to each heat pipe when the heat pipe fails.

2. Description of H-MMR system and simulation conditions

H-MMR is a hybrid system combining the micro modular reactor (MMR) with the concentrated solar power system (CSP) and the energy storage system (ESS) as shown in Fig. 1.

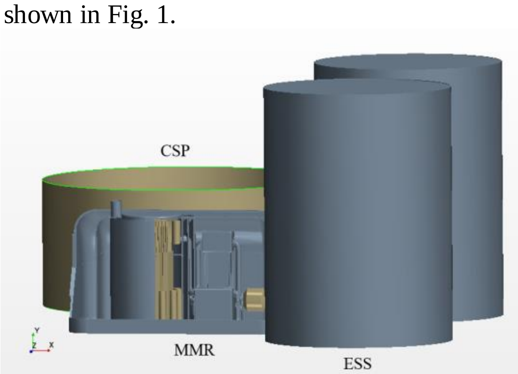

Fig 1. Simple configuration of H-MMR system

The previous MMR is developed to use a supercritical CO_2 of 20MPa as the primary coolant and secondary coolant simultaneously. In the H-MMR system, the design of MMR has changed overall. The heat from the reactor core is cooled by heat pipes so that it operates at atmospheric pressure. The heat pipes separate the active core region and sodium pool to avoid a reactor being affected by the coolant void reactivity. In the printed circuit heat exchanger (PCHE), the sodium transfers heat from the heat pipes to sCO_2 used to generate electricity (Fig. 2). The passive residual heat removal system (PRHRS) removes the residual heat by cooling the wall of the reactor vessel with air. The reactor core power is designed to have 18MWth for over 20 years without refueling. When it comes to the materials for fuel rod, UN fuel and ODS cladding are selected.

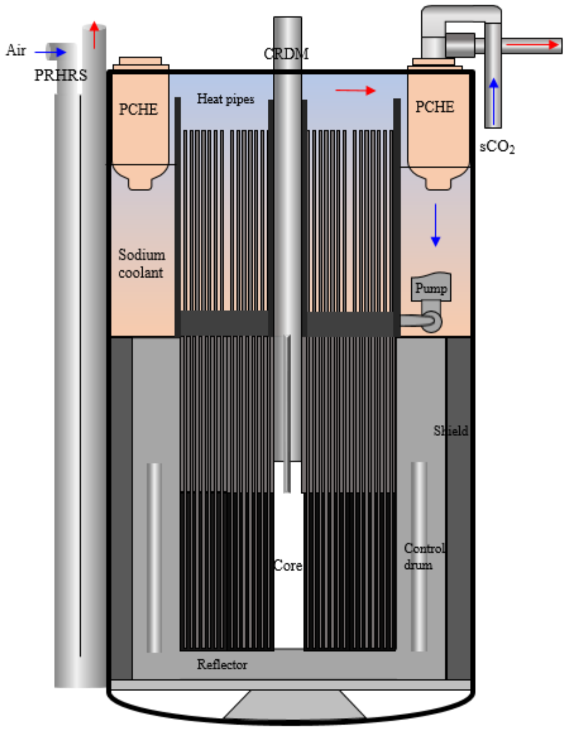

Fig. 2. Schematics of H-MMR core. PCHE, printed circuit heat exchanger; PRHRS, passive residual heat removal system, CRDM, control rod drive mechanism.

The operating temperature of heat pipe is determined by sodium pool temperature distributed from 602℃ to 650℃. Considering the temperature of fuel rod and operating limit of the heat pipe, it is preferable to use working fluid having a high operating limit under the low operating temperature. Therefore, potassium is selected for the working fluid because it has more marginal operating limits in the operating temperature of 660℃ (Fig. 3). The limitation of the heat pipe was calculated based on the five heat transport limitations [2].

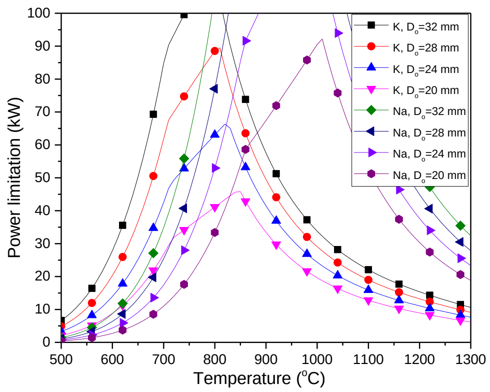

Fig. 3. Operating limits as a function of operating temperature for potassium and sodium heat pipe with a diameter of D_o and annular wick structure.

The heat pipe is applied to the reactor core, surrounded by fuel and cladding as indicated in Fig. 4. The active core height is 1.2m and the gap conductance in each interface is assumed to be 5000 W/m^2K as the gap conductance is about 5000 to 25000 W/m^2K depending on the height of the fuel [3].

Each hexagonal fuel produces 20.4 kW of heat on average. The H-MMR has a sufficient safety margin in terms of thermal power as the heat pipe is capable of removing the heat up to approximately 33 kW.

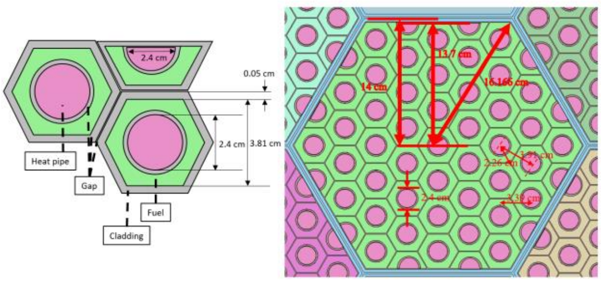

Fig. 4. Specific design parameters for the H-MMR core.

This study has investigated the temperature distribution and the applied heat to each heat pipe, using commercial computational fluid dynamics code STAR-CCM+. In particular, safety for the reactor core was evaluated when the heat pipe was damaged during operation.

3. Results and discussion

Fig. 5 reveals the temperature distribution under normal operating condition. The heat pipe number is indicated on the figure, e.g., number 1 means the central heat pipe and number 7 means the corner heat pipe. With the assumption that the power distribution follows the cosine power shape, all safety analyzes were performed at a height of 0.6 m where maximum thermal power is found. The maximum temperature is found at the edge of outer cladding, surrounding the fuel and heat pipe. Due to the semi-circular heat pipe installed in the corner, the temperature is well distributed along the fuel assembly.

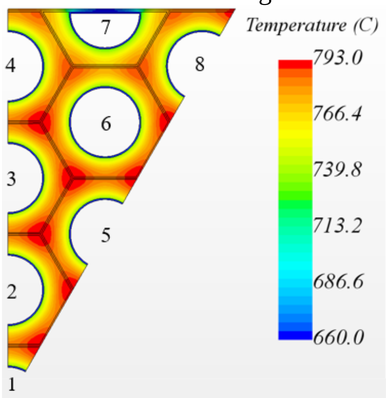

Fig. 5. Contour plot of temperature in the fuel assembly when the core height is 0.6m.

When the central heat pipe fails, the number 1 heat pipe could not remove heat from the center, more heat was applied to the adjacent heat pipe (Table. 1). For the heat pipe limitation, the failure did not cause damage to the surrounding heat pipes since the amount of heat is still below the operating limit, which is approximately 33 kW. The temperature of cladding adjacent to the broken heat pipe rose up to 1032℃, which is similar to the temperature of central fuel (Fig. 6). Although this temperature is below its melting temperature, the integrity of ODS cladding is not guaranteed above 800°C [4]. Therefore, the reactor should shut down to replace the broken heat pipe with a new heat pipe.

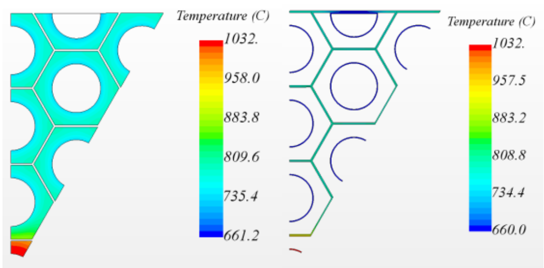

Fig.6. Contour plot of temperature in the fuel assembly for the failure of number 1 heat pipe.

The effect of the failure for the corner heat pipe is shown in Fig. 7. The temperature around the broken heat pipe is about 1000°C, and this trend was quite similar to the result when the central heat pipe broke. For the adjacent heat pipe, applied heat increased up to 26.8 kW.

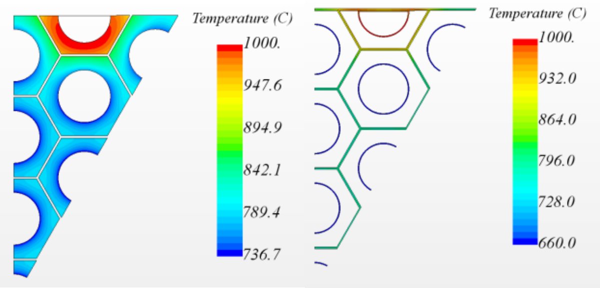

Fig.7. Contour plot of temperature in the fuel assembly for the failure of number 7 heat pipe

Heat pipe	Normal operation	Number 1 failure	Number 7 failure
Number	Applied heat (kW)	Applied heat (kW)	Applied heat (kW)
1	20.6	0.0	20.6
2	20.6	24.0	20.6
3	20.6	20.6	20.7
4	20.2	20.2	26.8
5	20.6	20.7	20.6
6	20.4	20.4	23.7
7	10.1	10.1	0.0
8	20.2	20.2	26.8

Table I. Applied heat to each heat pipe depending on the assumed conditions.

4. Conclusion

The H-MMR system using the heat pipes to transfer heat from the reactor core to PCHE was introduced. With given conditions described above, the temperature and heat applied to each heat pipe were obtained and the consequences of the heat pipe failure were analyzed with commercial computational fluid dynamics code.

In normal operation conditions, the heat pipes kept the temperature in a satisfactory range. It was observed that the heat removal capacity of the heat pipe was sufficient for the current design. To make more efficient H-MMR, the diameter of heat pipe needs to be optimized, considering temperature, heat pipe limitations and reactor lifetime.

Under the postulated accident, the damage to a heat pipe partially increased the fuel and cladding temperature. Since the operating temperature of cladding is lower than that of fuel, continuing to operate the reactor with the broken heat pipe cannot guarantee the integrity of the cladding because the temperature around the broken heat pipe exceeds 800°C. Meanwhile, there was no additional damage to the adjacent heat pipes right after the heat pipe failure because the heat applied to them is still below the limit. Therefore, it is expected that the reactor affords to shut down safely, using CRDM after the failure is detected.

Acknowledgements

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