Preliminary study on the passive cooling method for spent fuel storage pool for water-cooled SMRs

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1. Introduction

Small modular reactors (SMRs) are reactors with generation capacity below 300MWe that strongly rely on serial, factory-based production of reactor modules. The recent interest in small modular reactors is driven by a desire to reduce the total capital costs of nuclear power plants and to provide power to smaller/isolated grid systems than before [1].

Providing reliable spent nuclear fuel pool cooling became more important in light water reactors after the Fukushima accident. A successful water-cooled SMR will also have to address this issue. Unless SMRs claim to have no refueling during its service lifetime, most water cooled SMRs should have a strategy how to manage the used nuclear fuel.

In this paper, for the size of spent nuclear fuel from a water-cooled SMR, the size of the passive cooling system for the spent nuclear fuel pool is estimated. Two passive cooling methods are compared. One passive cooling method uses a heat pipe technology and the other passive cooling method uses a natural circulation loop.

2. Methods and Results

2.1 Thermal output of spent nuclear fuel pool

From the spent nuclear fuel design of recently licensed APR+, the water-cooled SMR spent nuclear fuel pool heat load is estimated. The maximum SMR spent nuclear fuel storage pool thermal output is assumed to be 13.3MWth in this study.

2.2 Cooling method using heat pipe

A heat pipe is a cooling device that transfers heat from a hot reservoir to a cold reservoir using capillary forces generated by a wick or porous material and phase change of a working fluid [2]. For near room temperature application, most of the heat pipes use ammonia, methanol, ethanol, or water as the working fluid.

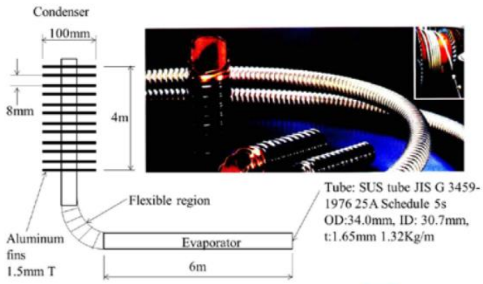

Fig. 1. Corrugated heat pipe [3]

The temperature of the final heat sink air is assumed to be 50°C, and the sensitivity analysis is performed for the temperature of the spent fuel storage pool from 60°C to 90°C. Ammonia is selected as the working fluid for heat exchange due to compatibility of the working temperature and evaporation and condensation temperatures of ammonia.

- $\mathrm{T_{SFP}} = T_{air} + \frac{Q_{spentfuel}}{n_{tube}} R_{th}$
- Total $\mathrm{R_{th}} = 0.0177°\mathrm{C/W}$ [3]

The number of heat pipes according to the target temperature of the spent nuclear fuel pool is calculated. However, it is noted that the change in the heat transfer coefficient as the target temperature changes is not considered. As the target temperature approaches to 50°C, it can be seen that the number of heat pipes increases exponentially.

Table I: Required number of heat pipes according to target pool temperature

Target temperature [°C]	Number of heat pipes
60	23,541
70	11,772
80	7,847
90	5,886

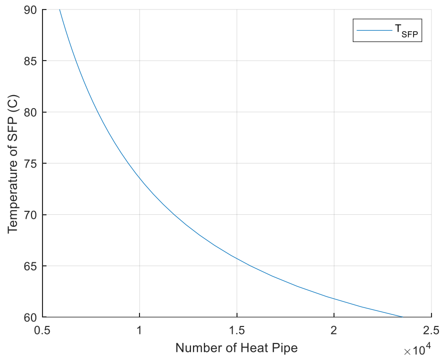

Fig. 2. Number of heat pipes required for cooling the spent nuclear fuel pool

2.3 Cooling method using a natural circulation loop

A method of passively cooling the spent nuclear fuel pool using a natural circulation loop with two heat exchangers is evaluated. When water is used in the natural circulation system, it is impossible to form a natural circulation system operating in between 12.35-19.95kPa condition for a height of 27m. This is because the pressure difference between the low-pressure part and the high-pressure part of the system differs by more than 270kPa with a height of 27m due to hydrostatic pressure. Therefore, ammonia is again used for the naturally circulating fluid.

- Saturation pressure of ammonia at 50°C: 2034.0 kPa
- Saturation pressure of ammonia at 60°C : 2615.6 kPa

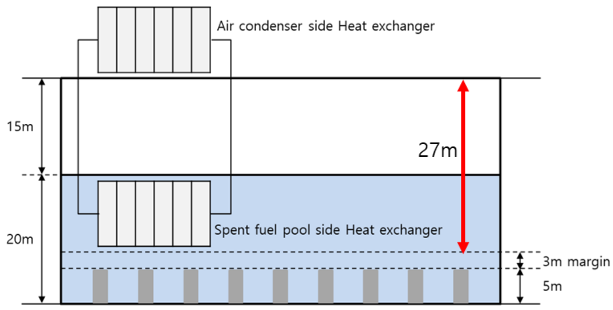

Fig. 3. Spent nuclear fuel pool using natural circulation cooling system

In order to calculate the amount of heat exchange, the following variables related to the heat exchanger are assumed.
- Tube inner diameter: 12mm
- Tube thickness: 2mm
- P/D ratio: 1.5
- Loop system pressure:(2034.0 + 2615.6)/2 = 2324.8kPa
- $\frac{1}{UA} = \frac{1}{h_1 A_1} + \frac{t}{kA_2} + \frac{1}{h_3 A_3}, A_1 = A_2 = A_3$ (assumed)
- Spent fuel pool side water velocity: 0.5m/s (assumed)
- Air condenser side air velocity: 5.0m/s (assumed, fan used)
- Stainless steel conductivity: 14 W/mK

- Ammonia side heat transfer coefficient (for Spent nuclear fuel pool side heat exchanger): 1281 $\mathrm{W/m^2}K$ [3]
- Ammonia side heat transfer coefficient (for Air condenser side heat exchanger): 8857 $\mathrm{W/m^2}K$ [3]

The water side heat transfer coefficient of the spent fuel pool side heat exchanger and the air side heat transfer coefficient of the air side heat exchanger are all calculated using the Dittus-Boelter equation.

- Spent nuclear fuel pool side heat transfer coefficient: 2795.9 $\mathrm{W/m^2}K$
- Air side heat transfer coefficient: 8857 $\mathrm{W/m^2}K$

Using the assumed values summarized above, the size of the heat exchanger required to cool 13.3MWth for the target pool temperature is obtained as follows.

Spent nuclear fuel pool side
- Required heat transfer area: 5341.6$\mathrm{m^2}$
- Required heat exchanger volume: 61.21$\mathrm{m^2}$
Air condenser side
- Required heat transfer area: 144905.7$\mathrm{m^2}$
- Required heat exchanger volume: 1660.5$\mathrm{m^2}$

The results of sensitivity analysis according to changing the target spent nuclear fuel pool temperature is as follows.

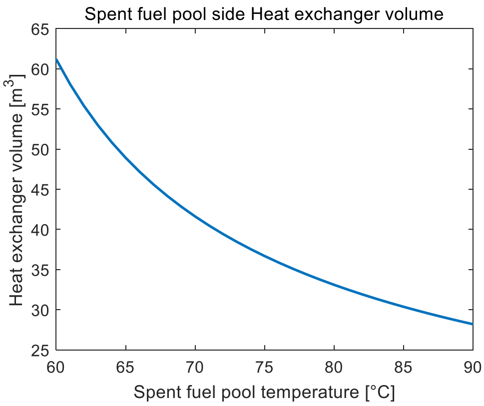

Fig. 4. Spent nuclear fuel pool side Heat exchanger volume according to the target pool temperature

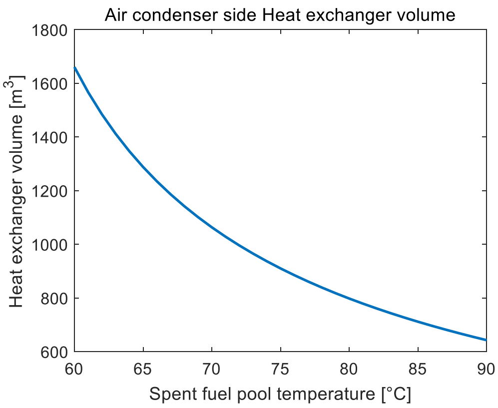

Fig. 5. Air condenser side Heat exchanger volume according to the target pool temperature

3. Summary and Conclusions

Two passive cooling methods of a water-cooled SMR spent nuclear fuel pool are evaluated. Although the temperature of the final heat sink air is assumed to be relatively high for conservative analysis, it is confirmed that excessively large number of heat pipes may be required for the spent nuclear fuel cooling for an SMR. In the case of a natural circulation loop case, it is observed that water may not be appropriate for the working fluid due to the mismatch of operating pressure and hydrostatic pressure. However, in the case of using ammonia as a working fluid, it is evaluated that the passive indefinite cooling can be the provided for a realistic system size when sufficient air velocity is guaranteed.

REFERENCES

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