Thermal Performance Evaluation of Spent Fuel Pool Cooling System with Water Jacket and Heat Pipe

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1. Introduction

Small Modular Reactors (SMRs) are a promising concept for generating nuclear energy. Among various SMR projects, NuScale showed outstanding performance with their innovative approach towards the licensing process. NuScale succeeded to get the regulatory approval from the Nuclear Regulatory Commission. NuScale suggested the concept of spent fuel pool (SFP) which store enough water to cool spent fuel during the station black out accident. However, the risk of fuel uncover still remains because the amount of water is limited. Also, with the increase of the reactor power, SFP should increase to store the spent fuel safely. This leads to the economical inefficiency.

In order to solve the problem, we suggested the concept of heat pipe and air cooling tower for the SFP cooling [1]. Installed heat pipe deliver the heat from the spent fuel to the air cooling tower and the air cooling tower release heat to the environment.

This cooling system aims to maintain the SFP temperature under the 60 degree of Celsius during the normal operating condition, and 90 degree of Celsius under the accident condition. During the normal operation, temperature of SFP and the outside air is small. Therefore, separated cooling system is necessary. We installed cooling fan for the cooling but the system with the separated cooling fan is complicated. As a consequence, we suggested simpler system using heat pipe and water jacket. The system is validated by in-house MATLAB code.

2. Methods

2.1 System Description

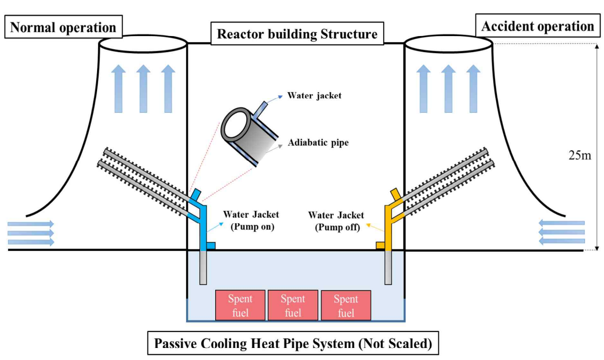

Fig. 1. Schematic figure of SFP cooling system for normal/accident operation

A heat pipe consists of an evaporator section, an adiabatic section, and a condenser section and utilizes the thermosiphon type. Each heat pipe has a condenser section consisted of seven fin tubes. The fin tubes increase surface area which leads to the higher heat transfer efficiency. We plan to install a water jacket in adiabatic section which act as a condenser section during normal operation. If the water circulation in the jacket is interrupted due to an accident, it revert to its original function as an adiabatic section. Instead, the condenser section connected to the cooling tower control the temperature of the spent fuel pool. The water jacket is consist of counter-current heat exchanger.

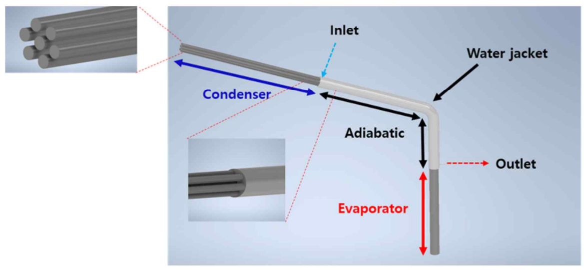

Fig. 2. Schematic figure of the heat pipe design.

Table I: Heat pipe specification information

	Evaporator	Adiabatic (water jacket)	Condenser
Outer diameter (m)	0.3185	0.3185	0.0891
Inner diameter (m)	0.3055	0.3055	0.0811
Length (m)	3.0550	6.1100	5.1900
Fin depth(m)	-	-	0.008
Fin thickness(m)	-	-	0.001
Distance between pins(m)	-	-	0.0027
Angle(°)	90	90 → 20	20
Material	stainless steel (STS316L 20S)		

To analyze the effect of the water jacket, MATLAB calculation was performed with varying the mass flow rate and the water temperature. The mass flow rate of 10 m^3/hr and 20 m^3/hr, and the water temperature of 20 ℃ and 30 ℃ cases were validated. The target scenario is the occurrence of the SBO after the 12 hours of normal operation of the water jacket. Twelve hours is sufficient time for the spent fuel pool to converge to a steady state. The number of heat pipes installed in the pool is 444. For the conservative evaluation, we assumed that the SMR was constructed in a desert region with air temperature of 50 ℃. Also moderate air temperature of 25 ℃ case was validated together. The decay heat generated from the spent nuclear fuel is 13.3 MWth.

2.2 Heat Transfer Calculation

To evaluate the cooling performance, whole system was divided into 450 nodes. During the normal operation, the calculation progress as Fig.3. We assumed the temperature of first node in the evaporator part and compute total heat transfer rate. The first node temperature in adiabatic(water jacket) part was calculated with the information at the final node of evaporator. Since the inlet temperature of the water jacket cooling water is fixed, outlet temperature of water jacket is calculated by the total heat transfer from evaporator. After the heat transfer rate calculation of adiabatic part, we compared the value with the heat transfer rate at the evaporator part. If the value is different, calculation go back to the first step which assumed the first node temperature of evaporator. The water temperature obtained from the calculation delivered to the next time step.

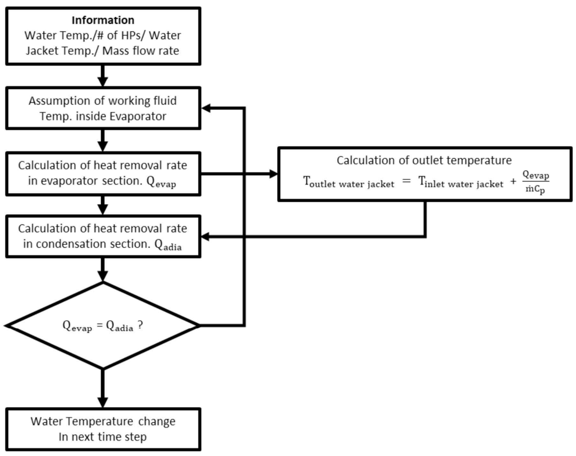

Fig. 3. Calculation algorithm of the heat pipe during normal operation.

The calculation algorithm for the accident scenario is shown in the Fig.4. The first node temperature of the condensation part was calculated considering the pressure drop in the adiabatic part. The heat transfer rate of condensation part was calculated by the temperature and the flow velocity in the cooling tower. If the heat transfer rates of the condensation part and the evaporation part are different, the calculation is repeated with different evaporation part initial temperature. If the value is identical, we compare the heat transfer rate at the condensation part and the cooling tower. The process is repeated until the heat transfer rate is identical. The correlation used in the code are summarized in Table 1.

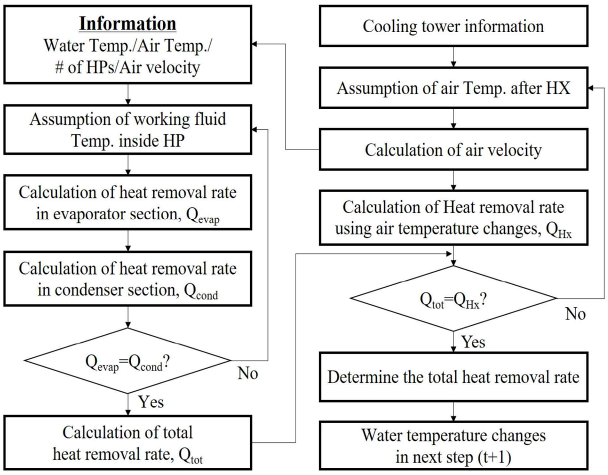

Fig. 4. Calculation algorithm of the heat pipe in accident situation.

Table II: Correlations used in the code[2].

	Inside of Heat Pipe	Outside of Heat Pipe
Evaporator	Shiraishi[3]	Churchil and Chu
Adiabatic	Chato	Dittus - Boelter
Condenser	Chato	Zukauskas

3. Results

The results with cooling tower air temperature of 25 ℃ is shown in the Fig.5. The modified heat pipe cooling system succeeded to maintain the SFP temperature below the target temperature for all cases. Even during the SBO scenario, the system maintained the SFP temperature below 90 ℃, ensuring the safety of the spent fuel pool without the separate power system. The results with the assumption of the air temperature of 50eh is shown on Fig. 6.

In all cases, the cooling system succeeded in maintaining the SFP temperature below 90 ℃. This means that the heat pipe cooling system can guarantee the safety of nuclear power plants anywhere in the world.

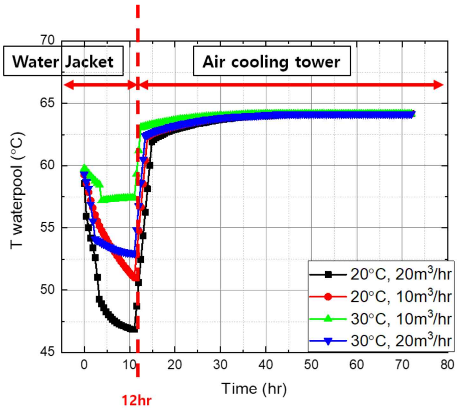

Fig. 5. Temperature of water pool change as function of water jacket temperature and mass flow rate in air temperature 25 ℃

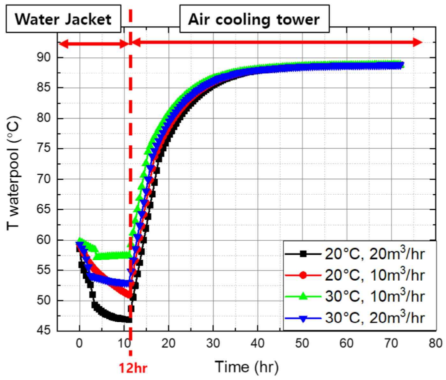

Fig. 6. Temperature of water pool change as function of water jacket temperature and mass flow rate in air temperature 50 ℃

4. Conclusions

New heat pipe and water jacket cooling system reduce the complexity of the original cooling system design without damaging the performance. We confirmed that the safety of the spent fuel pool is ensured during normal operation with the water jacket flow temperature under 30 ℃ and the mass flow rate over 10 m^3/hr.

For the validation of the accident scenario, we assumed both ordinary air condition (25 ℃) and desert air condition (50 ℃). The results showed that the safety of the spent fuel pool is ensured during the SBO. However, there still remains further works to improve the reliability of the calculation. The correlation used in the study should be validated in the condition of large diameter heat pipes. Also, the slope effect should be reflected. The further work will be conducted soon and will be presented in next KNS.

5. Acknowledgment

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