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Cooling Performance Evaluation of the Hybrid Heat Pipe for Spent Nuclear Fuel Dry Storage Cask

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1. Introduction

The capacity of spent nuclear fuel storage pool in Korea is expected to be almost saturated in 2024, although many actions were developed to increase the storage capacity such as high density storage rack. It is still insufficient for the about 20-30 tons of spent fuel generated from nuclear power plant every year [1]. In addition, fuel discharge burnup is increasing as fuel operation cycle becomes longer. Only spent fuel pool cannot satisfy the demands for high burnup fuel and large amount of spent fuel. Therefore, it is necessary to prepare supplement of the storage facilities. As one of the candidate of another type of storage, dry storage method have been preferred due to its good expansibility of storage capacity and easy long-term management.

Dry storage uses the gas or air as coolant with passive cooling and neutron shielding materials was used instead of water in wet storage system. It is relatively safe and emits little radioactive waste for the storage. As short term actions for the limited storage capacity of spent fuel pool, it is considered to use dry interim/long term storage method to increase the capacity of spent nuclear fuel storage facilities [2].

For 10-year cooled down spent fuel in the pool storage, fuel rod temperature inside metal cask is expected over 250 °C in simulation [3]. Although it satisfied the criteria that cladding temperature of the spent fuel should keep under 400 °C during storage period, high temperature inside cask can accelerate the thermal degradation of the structural materials consisting metal cask and fuel assembly as well as limitation of the storage capacity of metal cask.

In this paper, heat pipe-based cooling device for the dry storage cask was suggested for enhancement of the safety and storage capacity of the metal cask, which is called hybrid heat pipe. To evaluate the concept of the cooling device, 2-step CFD analysis was conducted for the cooling performance of hybrid heat pipe, which consists of single fuel assembly model and full scope dry cask model.

2. CFD Analysis

Heat pipe is the excellent passive heat transfer device using both principles of the conduction and the phase change [4]. It consists of the sealed metal pipe, working fluid, and wick structure. In evaporator section, working fluid is evaporated with absorbing heat, and vapor flows through adiabatic section, and after reaching condenser section, vapor is condensed and liquid go back to the evaporator section through wick structure by capillary force. With these characteristics, external power source for operation of the heat pipe is unnecessary. Figure 1 shows the schematic of the operation principle of general heat pipe.

2.1 Hybrid heat pipe

Hybrid heat pipe, which is a heat pipe containing neutron absorber was suggested for the passive cooling for nuclear applications [5]. With heat transfer characteristics of heat pipe, hybrid heat pipe can have capability of both removal of the decay heat and control the reactivity with neutron absorber. Hybrid heat pipe can be applied to nuclear applications such as passive in-core cooling system substituting control rod for advanced nuclear power plant, wet storage pool and dry storage cask for spent nuclear fuel. In this study, hybrid heat pipe was applied to metal cask type dry storage facility. 2 cases of hybrid heat pipe applications were analyzed, which are 1 hybrid heat pipe per 1 SNF assembly at the center instrumental guide tube and 5 hybrid heat pipes per 1 SNF assembly at 4 guide tubes and 1 instrumentation tube. Figure 2 shows the schematic of the heat pipe-equipped dual purpose cask for dry storage of spent fuel.

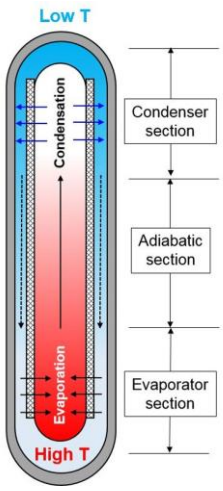


Fig. 1 Operation of heat pipe

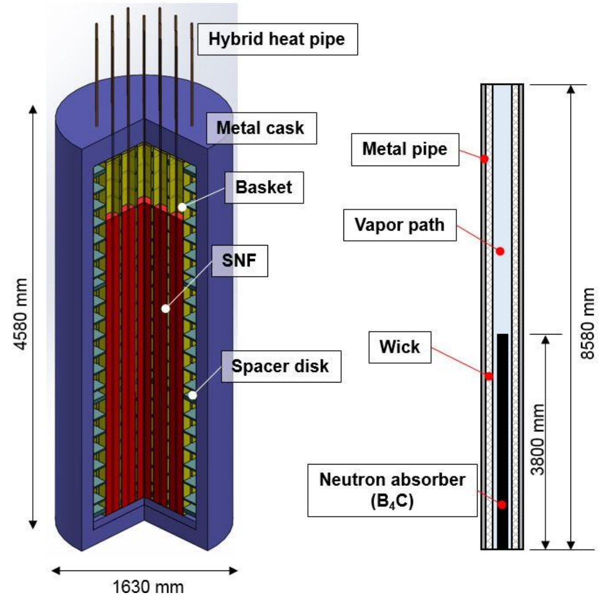


Fig. 2 Hybrid heat pipe equipped dry storage cask

2.2 CFD Modeling

To evaluate the thermal performance and heat removal capacity of the heat pipe-based cooling device for dry cask, 2-step CFD analysis was performed, which consists of single fuel assembly model and full scope dry cask model. In single fuel assembly simulation, phase change heat transfer of the working fluid inside heat pipe was fully calculated to get the heat removal capacity in dry storage condition. Based on the results of single fuel assembly analysis, full scope dry cask simulation was conducted for examining effects of overall cooling performance of the hybrid heat pipe on the dry storage cask.

2.2.1 Single fuel assembly model

In the single fuel assembly model, 1/8 model of 16 ×16 CE type PWR spent fuel was considered. Decay heat generated was 1.0 kW per SNF assembly applied as constant heat flux at the fuel rod surface, 35 W/m^2 of which the amount of decay heat is equivalent to the spent fuel cooled by pool for 10 years. Considering natural circulation flow inside metal cask, inlet velocity and temperature was set as 0.2 m/s and 50 °C, respectively. For working fluid, water with saturation state as 50 °C and 0.12 bar was set with thermal phase change at saturation temperature for liquid and vapor state. For wick structure, porous media was set with porosity 0.62 and permeability 1.92×10^{-10} m^2 corresponding 100-mesh stainless steel screen mesh for calculating momentum loss.

2.2.2 Full scope dry cask model

Full scope dry cask consists of the metal cask, basket, and spacer disk. Basket is steel duct to support the fuel assembly with 222 × 222 mm cross section, of which height is 4550 mm. Gap between baskets was set as 30 mm. In CFD model, basket was considered as thin material with thickness 5 mm between spent fuel assembly and helium gas, and spacer disk was neglected in this study. Diameter and height of the metal cask is 1.63 m and 4.58 m, respectively. Spent fuel assembly was considered as porous media with pressure loss coefficient of 25 in the axial direction and 2500 in the transverse direction. Decay heat generated was set as constant volumetric heat source about 6.2 kW/m^3, equivalent to 1.0 kW per assembly. Fluid inside metal cask is helium gas at 1 bar with a reference temperature of 320 K. Side wall of metal cask was set as 320 K.

3. Results and Discussion

To validate the CFD model, results were compared for normal dry cask and single fuel assembly with results by In et al [3]. Figure 3 shows the temperature and velocity contours of the single fuel assembly simulation. Compared with In et al.'s results, results showed good agreements in the velocity and temperature profile. For full scope dry cask simulation, there were good agreements in temperature and velocity prediction inside dry cask without heat pipe cooling. Natural circulation flow of the helium inside metal cask formed upward flow in the assembly and downward flow at the side of dry cask.

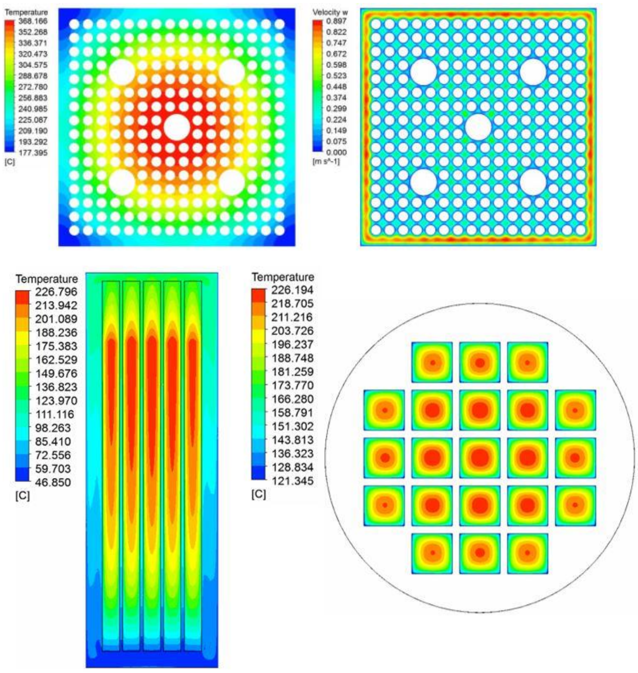
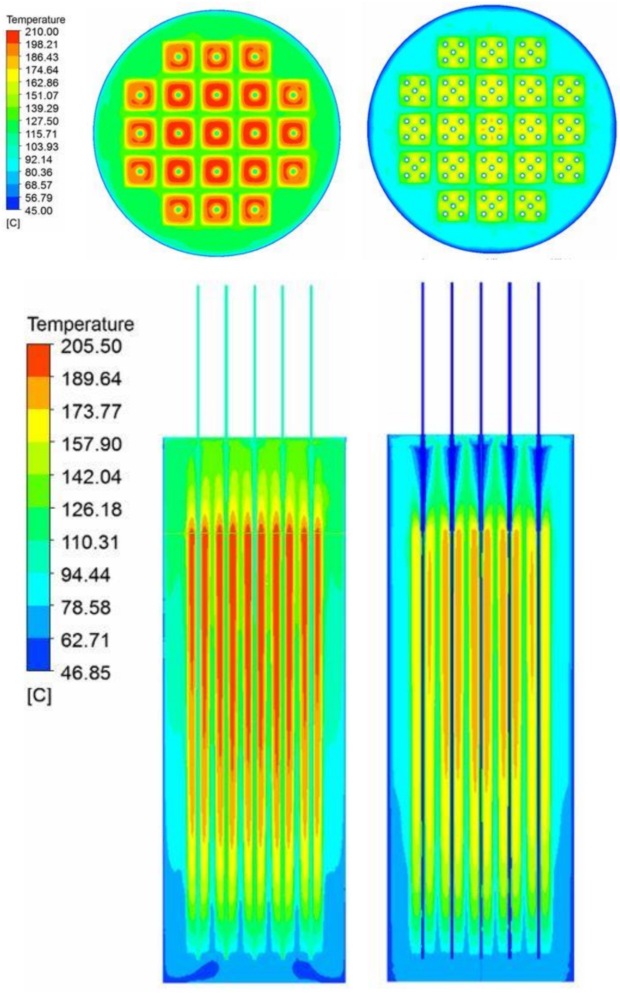


Fig. 3 Temperature and velocity contours of the SNF assembly and full scope dry cask without hybrid heat pipe

Effective thermal conductivity model was adjusted for heat pipe based on the results of the single fuel assembly analysis. Compared with results of full calculation of phase change phenomena in heat pipe, heat pipe with effective thermal conductivity model can also predict the temperature inside spent fuel assembly. Therefore, the heat pipe was modeled as effective thermal conductivity with 1000 W/m K consistent with heat transfer capacity used in the full scope dry cask simulation. In single fuel assembly simulation of case 1 (1 hybrid heat pipe applied per assembly), one hybrid heat pipe had heat removal capacity about 167 W. For case 2 (5 hybrid heat pipe applied per assembly), hybrid heat pipe at the center instrumentation tube can remove 110 W and another located at the guide tube can remove 103 W. Heat removal capacity for each hybrid heat pipe was adjusted to the full scope dry cask simulation as equivalent thermal conductivity.



(L) 1 HP / 1 SNF assembly (R) 5 HP / 1 SNF assembly

Fig. 4 Temperature contour of the (L) case 1 (1 HP /assembly) and (R) case 2 (5 HP/ assembly)

Figure 4 shows the temperature contours of the case 1 and case 2 simulation of full scope dry cask. For case 1, total 21 hybrid heat pipes were installed, and its maximum helium temperature inside cask was 205.5 °C. Compared with the normal dry cask, maximum temperature decreased as 10.0 %. For case 2, total 106 hybrid heat pipes were applied, and its maximum helium temperature inside cask was 170.9 °C reducing 20.5 % of helium temperature compared with normal case. Maximum fuel temperature was estimated to 290 °C for normal case. Compared with normal case, maximum fuel temperature was low for both cases, which was estimated about 262 °C for the case 1 and 195 °C for case 2, respectively. Therefore, hybrid heat pipe can increase the safety margin of the dry cask and enhance storage capacity with decreasing overall helium temperature and maximum fuel rod temperature. Table. I shows the summary of the 2 step analysis of hybrid heat pipe for dry cask.

Table I: Summary of the hybrid heat pipe performance

	Normal (no HP)	Case 1 (1 HP / assembly)	Case 2 (5 HPs / assembly)
He T_{avg}	265.4 °C	252.1 °C	160.3 °C
Fuel T_{max}	290.0 °C	261.6 °C	195.1 °C
$Q_{removed}$	-	IT: 167 W	IT: 110 W
		GT: -	GT: 103 W

(IT: Instrumental tube, GT: Guide tube)

3. Conclusions

As a passive cooling device of the metal cask for dry storage of spent nuclear fuel, hybrid heat pipe was applied to DPC developed in Korea. Hybrid heat pipe is the heat pipe containing neutron absorber can be used as a passive cooling in nuclear application with both decay heat removal and control the reactivity. In this study, 2-step CFD analysis was performed to find to evaluate the heat pipe-based passive cooling system for the application to the dry cask. As a result, key findings are as follows:

1) CFD model of the metal cask for dry storage was constructed and validated.
2) For the heat pipe simulation, effective thermal conductivity model, which was set the heat pipe as a solid having thermal conductivity equivalent with heat transfer capacity was adopted and it can predict the temperature inside metal cask.
3) For the case 1 (1 hybrid heat pipe applied per assembly), 1 hybrid heat pipe can remove the decay heat about 163 W, decreasing maximum helium temperature to 205.5 °C inside metal cask.
4) For the case 2 (5 hybrid heat pipes applied per assembly), hybrid heat pipe located at the center instrumental guide tube have heat transfer

capacity as 110 W and other 4 hybrid heat pipes located at the guide tube can remove 103 W each, decreasing helium temperature to 170.9 °C inside metal cask.

5) Maximum fuel temperature for case 1 is 261 °C, and 195 °C for case 2 respectively, which shows the increase of thermal margin for fuel temperature compared to that of normal case about 290 °C.
6) Heat pipe-based passive cooling device can increase the safety margin of the dry storage cask, has potential to enhance the storage capacity of the dry cask even for high burnup SNF assemblies, as well as prevent to accelerate the degradation of the structural materials under dry storage condition.

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