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Enhanced Thermal Management System for Spent Nuclear Fuel Dry Storage Canister with Hybrid Heat Pipes

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1. Introduction

Storage capacity of the spent nuclear fuel pool in Korea is expected to be saturated in 2024 [1]. In addition, fuel burnup keeps increasing as fuel operation cycle becomes longer than before for efficient fuel resource utilization [2]. Considering issues on the spent nuclear fuel in Korea, strategy on spent nuclear fuel storage has been developed in various ways such as introduction of high density storage rack for spent nuclear fuel pool and dry storage cask. Dry storage uses the gas or air as coolant within sealed canister with neutron shielding materials. Dry storage system for spent fuel is regarded as relatively safe and emits little radioactive waste for the storage, but it showed that the storage capacity and overall safety of dry cask needs to be enhanced for the dry storage cask for LWR in Korea.

For safety enhancement of dry cask, previous studies of our group firstly suggested the passive cooling system with heat pipes for LWR spent fuel dry storage metal cask [3]. As an extension, enhanced thermal management systems for the spent fuel dry storage cask for LWR was suggested with hybrid heat pipe concept, and their performances were analyzed in thermal-hydraulic viewpoint in this paper.

2. Thermal Management Strategies for Dry Cask with Hybrid Heat Pipes

In this section, various types of hybrid heat pipe cooling systems for spent fuel dry storage canister was described in detail. Hybrid heat pipe is innovative heat pipe contains neutron absorber materials inside for nuclear applications, so that it has both neutron reaction control and passive cooling functions [4]. For the criticality control and thermal management for spent fuel dry storage, hybrid heat pipes can contribute safety enhancement for the currents dry canister design.

2.1 Issue on current design of dry cask

Current design of the dry canister consists of the metal cask, basket, and spacer disks. Spent fuel assemblies located inside each basket to maintain their positions, and spacer disks supports axial positon of the basket. Helium gas is charged in sealed cask and transport decay heat from spent fuel to cool of the air outside. Although there is no specific cooling device rather than helium and air natural convection cooling, proper gap between baskets, heat transfer fin of metal cask and air inlet design in concrete cask can give cooling function with satisfying safety criteria of dry storage cask.

In design of the dry storage cask, criteria should be satisfied in terms of 1) criticality analysis; 2) Radiation shielding; 3) Structural analysis; and 4) Thermal analysis. Especially, each component of the dry storage cask has its own temperature limit according to ACI 349 and ASME Code section III Div. 1. Table I shows the temperature limit for the dry storage canister. [5]

Table I: Temperature limit of the dry storage cask [5]

		Normal	Off-normal /Accident
Cask body	Metal	371 °C	538 °C
	concrete	Local 93 °C / Bulk 65 °C	176 °C
Disk		427 °C	538 °C
Absorber		399 °C	482 °C
Cladding		400 °C	572 °C

However, current design of the dry cask designed for 10-year cooled spent fuel in pool is expected to have its maximum temperature over 250 °C in fuel temperature [6]. Although this value satisfies safety criteria for dry cask, which maximum cladding temperature maintains under 400 °C, high temperature environment of dry cask can accelerate the thermal degradation of structural materials as well as limit overall storage capacity of dry cask. Therefore, it showed that current design of the dry cask needs to be improved in thermal management viewpoint to assure long-term integrity and achieve design lifetime.

2.2 Hybrid heat pipe for spent fuel dry cask

Heat pipe is the excellent passive heat transfer device using both principles of conduction and phase change of the working fluid [7]. With same working principles, hybrid heat pipe is suggested in UNIST thermal-hydraulic and reactor safety laboratory for the nuclear applications, shown in Fig. 1. In previous study [3], hybrid heat pipe cooling system applied to metal cask type dry storage cask was analyzed in CFD simulation and it showed that maximum fuel temperature was reduced about 30 °C with hybrid heat pipe system.

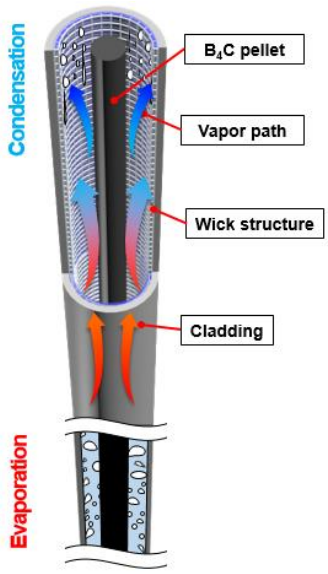


Fig. 1 Schematics of hybrid heat pipe

However, hybrid heat pipe design could be the weakest part of the dry cask due to exposed section for the air cooling of hybrid heat pipes, which could provide one of paths to release of radioactive materials. In this study, revised design with satisfying both cooling function and structural integrity was suggested with changing cooling section of the hybrid heat pipe to have lid of dry canister.

Revised design of hybrid heat pipe consists of two parts, which are heating section and cooling section. Heating section of hybrid heat pipe is the inserted part inside dry cask located inside guide tube or instrumentation tube of fuel assembly containing neutron absorber. In this part, working fluid charged in hybrid heat pipe evaporates, and vapor flows upward due to temperature difference. Cooling section of hybrid heat pipe has similar shape of canister lid, but have vacant space inside for working fluid flow. After reaching vapor from heating section, working fluid is condensed from temperature difference and liquid goes back to heating section from cooling section. This circulation of working fluid can transfer heat efficiently from spent nuclear fuel to outside with principle of phase change.

Revised design of hybrid heat pipe can be applied in both types of dry cask such as metal and concrete type, because hybrid heat pipe is designed for canister and does not need to modify existing cask design, so that any type of cask can adopt enhanced cooling concept with hybrid heat pipe. With hybrid heat pipe, dry cask can be free for the dependency of air natural cooling performance as well as have additional control system for criticality with neutron absorber inside hybrid heat pipe. Fig. 2 shows the revised design of the hybrid heat pipe applied to dry storage cask.

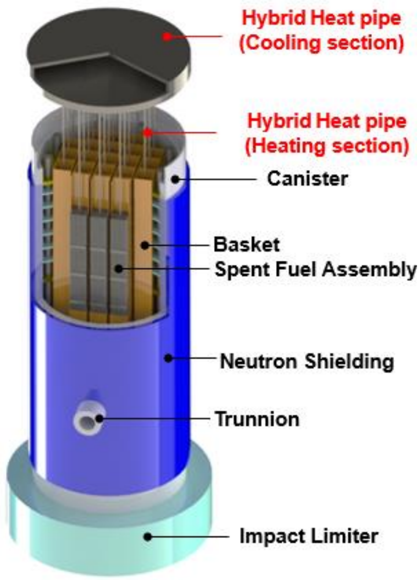


Fig. 2 Design of dry storage cask for LWR fuel with hybrid heat pipe (upper impact limiter was omitted.)

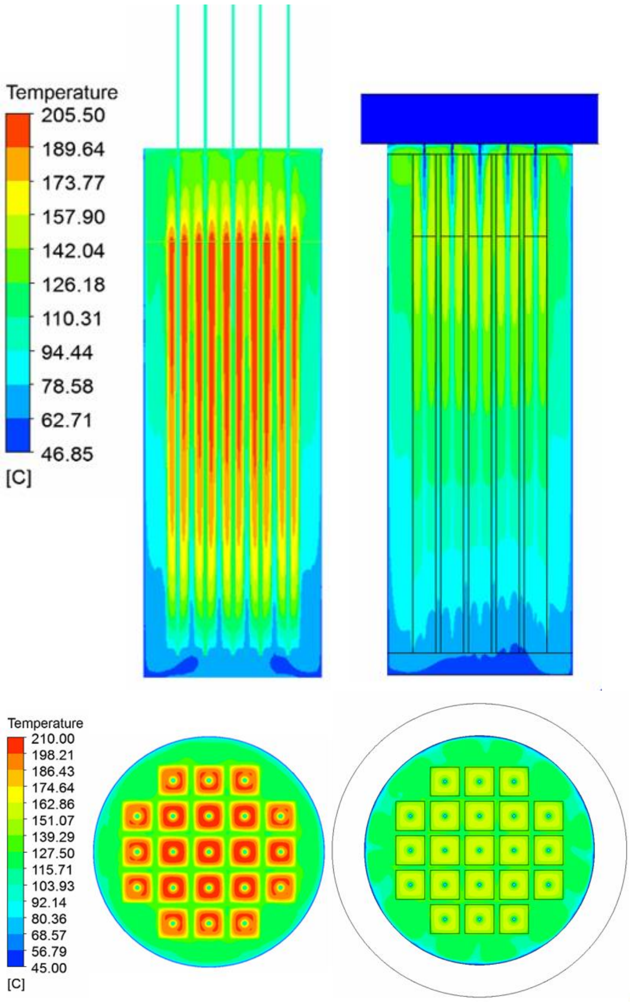
2.3 Thermal performance of revised hybrid heat pipe

To analyze the thermal performance of the revised hybrid heat pipe design to dry cask, CFD analysis was performed to evaluate thermal performance of revised hybrid heat pipe design applied to dry canister. In this study, both section of hybrid heat pipe was set as solid having effective thermal conductivity corresponding to hybrid heat pipe design without simulating phase change of working fluid to save computational resources. Effective thermal conductivity can be obtained from considering decay heat generated by spent nuclear fuel and heat transfer through helium inside canister and air outside canister. In simulations, canister side wall temperature was set to 40 °C as normal condition for both design.

For previous bundle type design of hybrid heat pipe, maximum helium temperature is 205.5 °C. For revised design, maximum helium temperature is 175.5 °C, having overall temperature inside canister. Since integrated type of revised design had larger area of cooling section, it had lower temperature gradient than that of bundle type. Therefore, with same effective thermal conductivity of hybrid heat pipe, total amount of heat removal for integrated type was lower than that of bundle type one. Fig. 3 and table II showed the comparison of design of hybrid heat pipe by CFD simulation.

Table II: Summary of hybrid heat pipe design simulation

	Previous (bundle type)	Revised (Integrated type)
Max. He T	205.5 °C	175.5 °C
Q_{HP}	1554.6 W	902.8 W



(a) Bundle type (b) Integrated type

Fig. 3 Axial and lateral temperature contours of dry canister with hybrid heat pipe design

3. Conclusions

In this paper, hybrid heat pipe concept for dry storage cask is suggested for thermal management to enhance safety margin. Although current design of dry cask satisfies the design criteria, it cannot be assured to have long term storage period and designed lifetime. Introducing hybrid heat pipe concept to dry storage cask designed without disrupting structural integrity, it can enhance the overall safety characteristics with adequate thermal management to reduce overall temperature as well as criticality control.

To evaluate thermal performance of hybrid heat pipe according to its design, CFD simulation was conducted and previous and revised design of hybrid heat pipe was compared in terms of temperature inside canister. As a result, revised design of hybrid heat pipe has similar cooling performance with previous bundle type one, which showed even lower temperature inside canister. Maximum helium temperature decreased as 25 °C and total heat removal amount was 902.8 W, which was the 5 % of overall capacity of canister. Therefore, revised design of hybrid heat pipe having integrated cooling section for the use of lid can have adequate cooling performance for the dry storage canister and further, it can contribute enhancement of safety for dry storage canister in terms of thermal management as well as criticality control.

ACKNOWLEDGEMENTS

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