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Enhanced Thermal Margin of Spent Fuel Dry Storage Cask Using Hybrid Control Rod

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1. Introduction

Amount of the spent fuel increases with increase of construction and operation of nuclear power plants. Reprocessing technologies and fast reactors are under development for reduction of nuclear waste. The spent fuels have been stored in storage facilities such as spent fuel wet storage and dry storage. Although the spent fuel removed from the core would be stored in water pool, its space is limited. Therefore, interim storage facilities are developed in the manner of dry storage cooled by air convection and radiation to maintain the temperatures of fuel cladding, basket, canister, concrete, and canister below the thermal limits [1].

Analyses of the dry storage cask at normal, off-normal, and accident conditions have been conducted for the appropriate design in terms of thermal, radiation, criticality, and material [2,3]. The analyses results guarantee the integrity of casks in present designs, however, the material problems are not validated with long-term operation at high temperature environment. Cooling capacity enhancement of spent fuel dry storage cask can mitigate the possible material problems retaining the additional thermal margin and storage capacity. Thus, new design of spent fuel dry storage cask using hybrid control rod (UCAN, UNIST canister) was designed [4]. The hybrid control rod is a combination of heat pipe and control rod [5]. Thermosyphon heat pipe is a passive heat transfer device using phase change of working fluid inside the container having different temperature interfaces. Inclusion of neutron absorber inside the heat pipe is a hybrid control rod which takes roles of neutron absorption and decay heat removal. Installation of hybrid control rod to spent fuel dry storage cask with condenser lid could provide additional decay heat removal path and homogenous neutron absorption maintaining the subcriticality.

In this paper, effects of hybrid control rod and heat sink design on the temperature margin of spent fuel dry storage cask were experimentally studied with scaled-down mockup to evaluate the efficiency of the changed design in comparison with general form of storage casks.

2. Experimental Setup

A mock-up was designed to be scaled-down to 1/10 of dimension of metal cask developed by KORAD in Germany as shown in Fig. 1. Total 21 baskets including cartridge heaters were installed to simulate the decay heat of spent fuel. Heat pipes located at the center of each basket and they were connected to the condenser lid. Gap between canister and cask wall was also considered in design. UCAN modifies the upper lid of cask by replacing it with condenser which contains heat sink medium. Four thermocouples inside the canister measure the air temperatures through the radial and axial directions. A K-type thermocouple was installed inside the condenser and two were deposited on the walls of cask and condenser for the measurement of temperature evolutions and heat transfer rates at each part. The experimental conditions are presented in Table I. At the same power density level, the temperature evolutions of the canister, basket, and condenser (or lid) were measured to observe the effect of hybrid control rod at steady state. The power density level of the experiment is maintained about 15 % of full scale cask due to material problem of the mock-up.

The material of cask, canister, and condenser is acrylic. Therefore, the relatively low power density was applied to the mock-up for the maintenance of mock-up integrity, and the distortion in heat transfer exist. Experimental works presented in this paper is preliminary test to compare UCAN and normal metal cask in terms of qualitative thermal margin.

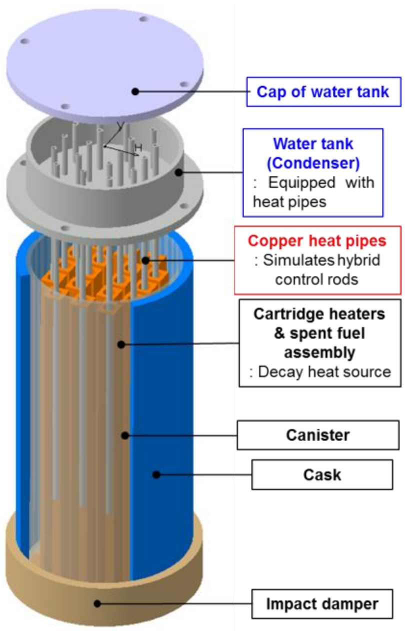


Fig. 1. Schematic of UCAN mock-up.

Table I: Experimental conditions

Controlled parameters	Notes	
Power density	0.93 kW/m^3 (90 W)	
Heat sink	Air	Water
Heat removal	Air	Heat pipe

3. Results and Discussion

3.1 Effect of Heat Pipe

The effect of heat pipe on temperature evolutions at transient phase and temperature distributions at steady state were measured with comparison of normal cask (decay heat removal by air convection and radiation at the walls). Temperature evolutions of normal cask was plotted in Fig. 2. Air temperatures at condenser and inside the canister were 80 °C and 95 – 110 °C. Wall temperatures at cask and condenser changed similarly to each other because the radiation and convection through radial direction is a main decay heat removal path of the cask. The axial temperature gradient inside the canister was also observed. TC-H-01, 02, and TC-L-01, 02 are positioned at the elevations of 350, 250, 200, 150 mm from the bottom of cask. The highest air temperature was measured at the highest elevation due to the density difference of the air according to temperatures.

Fig. 3 shows the variations of temperatures at each part of UCAN having heat pipes and heat sink medium as air. Air temperature at condenser lid reached 100 °C at steady state. Temperatures of air inside canister were 88 – 105 °C. Condenser wall temperature was always higher than that of cask wall which means the decay heat was transported to heat pipes and condenser (axial direction). The axial temperature gradient from the lowest elevation to condenser section was lower than normal cask. The axial heat transfer reduces the canister temperature and increases condenser temperature guaranteeing the extended temperature margins of canister compared to normal cask. Hence, it is advantageous in terms of integrity of material in long term operation.

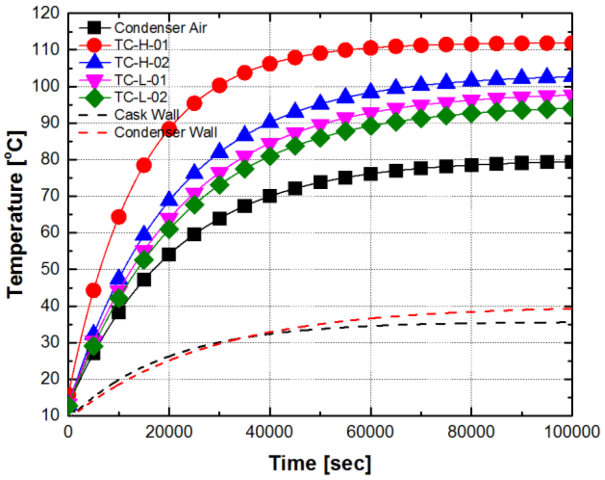


Fig. 2. Temperature evolutions of normal canister (without heat pipe)

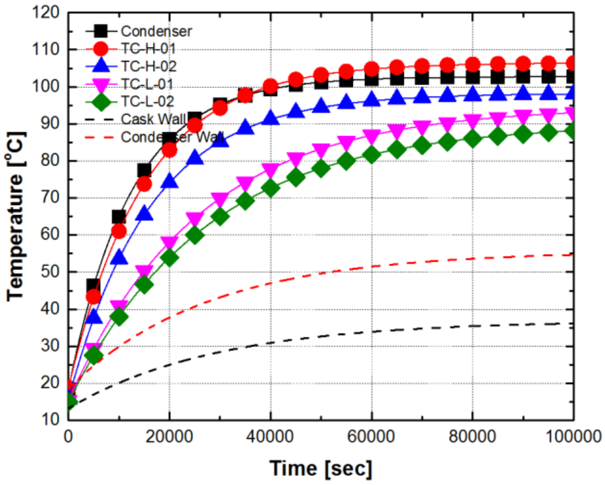


Fig. 3. Temperature evolutions of heat pipe-equipped canister with air condenser.

3.2 Effect of Heat Sink

For the magnification of heat pipe effect, water was used as heat sink medium in condenser. Fig. 4 describes the temperature variations of UCAN including heat pipe and water condenser. When the condenser is charged with water, the temperature increase rate was reduced compared to normal cask and UCAN with air condenser. The reduction of temperature increase rate was attributed to the high specific heat capacity of the water. At steady state, the water temperature reaches 90 °C. The lower heat sink temperature made the higher temperature gradient between evaporator and condenser section of heat pipe, and it enhanced the axial heat transfer. Inside temperatures of canister were 75 – 80 °C, which are significant lower temperatures in comparison with normal cask. In terms of axial temperature gradient of canister, water condenser showed lower gradient than air condenser and normal cask. Thus, the heat sink medium which has high specific heat is preferred in the design of UCAN to extend the temperature margin of canister.

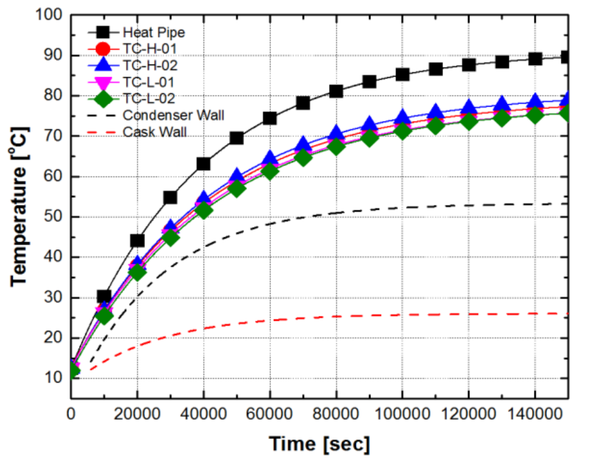
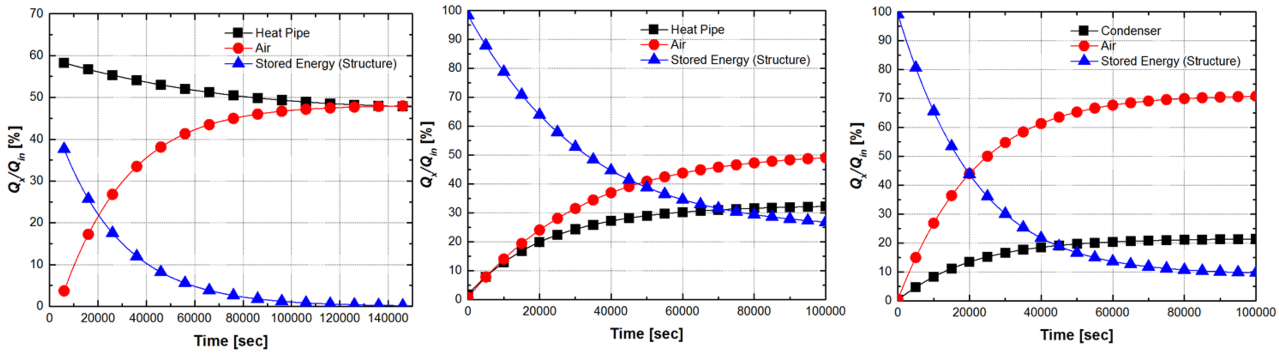


Fig. 4. Temperature evolutions of UCAN comprises water condenser and heat pipe.



(a) UCAN with water condenser (b) UCAN with air condenser (c) Normal cask

Fig. 5. Variations of heat transfer rates according to design of canisters.

3.3 Heat Transfer Rates

To analyze the heat transfer rates for each part, below energy balance equation was established:

$$\dot{Q}_{in} = \dot{Q}_{Condenser} + \dot{Q}_{structures} + \dot{Q}_{rad,1} + \dot{Q}_{rad,2}$$
$$= m_{H_2O} c_{p,H_2O} \frac{(T_{\tau+1} - T_{\tau})}{dt} + m_{air} c_{p,air} \frac{(T_{\tau+1} - T_{\tau})}{dt}$$
$$+ m_{acrylic} c_{p,acrylic} \frac{(T_{\tau+1} - T_{\tau})}{dt} + \sigma\varepsilon A_{Cond} \left(T_{H_2O}^4 - T_{env}^4\right) + \sigma\varepsilon A_{Wall} \left(T_{air}^4 - T_{env}^4\right)$$

where $\dot{Q}$ is heat (subscript in, condenser, structures, rad mean heat input, stored energy at heat sink medium of condenser, structures, and radiations through cask and condenser), m is mass, c_p is specific heat capacity, T is temperature, A is surface area, σ is Stefan-Boltzmann constant, and ε is emissivity. It was assumed that the heat input is converted to stored energy of structures such as basket, canister, cask, and condenser with radiation heats from cask wall and condenser wall to environment. Based on the measured temperature evolutions and information about designed structures, the heat transfer rates were calculated as shown in Fig. 5. Stored energy of structures was dominant at the initial phase of operation for the cases of UCAN with air condenser and normal cask. At the steady state of normal cask, heat input was converted to radiations through condenser (20 %) and cask wall (70 %) except 10 % (to structures). The ratio between radiations through condenser and cask wall corresponds to ratio of surface area. While UCAN with air condenser showed the radiation through condenser was increased to 30 % because the enhanced axial heat transfer by heat pipes made higher temperature at condenser section, consequently, higher radiation heat transfer rate at condenser section. The radiations through condenser section and cask wall were 50%:50% for UCAN with water condenser. It demonstrates that the heat removal at the outer wall of cask would be reduced when the heat pipes were applied to the canister and it could reduce the temperatures inside the basket and canister.

3.4 Efficiency of Heat Pipe

For the accurate analysis of effect of hybrid control rod on the thermal margin and spent fuel storage capability, the power densities forming the similar temperature distributions at steady states with water condenser-equipped UCAN were found by iterative experiments. Table II summarizes the experimental results. UCAN having condenser filled with water showed the highest power density to achieve average temperature of 80 °C inside the canister. The power density of UCAN with water condenser was 1.63 times of the normal cask. Thus, UCAN design could extend the thermal margin and spent fuel storage capacity of the cask. In aspect of axial temperature gradient, UCAN reduced the gradient which could reduce the thermal strain exerted on fuel rods due to temperature gradient.

Table II: Power densities of similar temperature distributions at steady states and its status

Type	Power density	Normalized axial temp. gradient
UCAN with water condenser	0.93 kW/m^3	1
UCAN with air condenser	0.72 kW/m^3	1.13
Normal cask	0.56 kW/m^3	2.33

4. Conclusions

For the enhancement of thermal margin and spent fuel storage capacity of the dry storage cask, UCAN design was proposed with installation of hybrid control rod and condenser lid. The effect of hybrid control rod on thermal behavior of the cask was experimentally studied. Followings are derived from experimental results:

(1) Hybrid control rod enhanced the decay heat removal rate in axial direction reducing the canister temperature.
(2) Heat sink medium determines the heat removal capacity of the hybrid control rod and efficiency of the UCAN system. The efficiency of UCAN system

increased as specific heat capacity of the heat sink increases.

(3) UCAN design achieved about 1.63 times of thermal margin and spent fuel storage capacity compared to normal cask design.

(4) UCAN design could reduce the thermal strain induced by axial temperature gradient because the design reduces the gradient.

ACKNOWLEDGEMENTS

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