Thermal Performance Test Facility for Nuclear Battery from a Conventional Dry Cask Using Hybrid Heat Pipe

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1. Introduction

As interest in carbon neutrality increases due to the concerns of global warming, the energy systems that can power generate without emitting greenhouse gases are getting attention. As one of the energy systems, UNIST suggested the Nuclear battery concept using a conventional dry storage cask equipped with hybrid heat pipes to increase the safety and capacity and to improve energy reuse [1]. The Hybrid heat pipe is a passive heat removal device that conducts the function of both heat transfer and reactivity control that contains neutron absorbing material in the evaporator. The neutron absorber in the evaporator section of the heat pipe plays a role as a reactivity control and additional heat transfer capacity of dry storage cask through the phase change, therefore, dry storage cask could be maintained the thermal margin and sub-criticality [2]. Through this passive heat transfer device, dry storage cask can meet the safety acceptance criteria provided by US NRC such as structural integrity, heat removal, confinement, shielding, maintaining sub-criticality, and material during the operation period. Simple design changes to the lid of conventional dry storage cask allow for effective heat management. The Hybrid heat pipe is located in the center of each fuel assembly, enabling axial heat transfer through the heat pipe as well as radial heat transfer through convection and radiation heat transfer by helium gas, increasing the possibility of recycling the waste heat. This advantage can be more useful for recycling waste heat without design changes by combining conventional dry cask with Stirling engines or thermal electric generation devices [3, 4].

In this paper, thermal-hydraulic analysis of dry cask combined with hybrid heat pipe was conducted to investigate enhanced decay heat cooling performance and figure out the heat recycling as a nuclear battery on the experimental results of the 1/5 scaled test facility of dry cask for the spent nuclear fuel storage. These results will be used to verify the design of UCAN can enhance the safety of dry storage cask and use recycle waste heat while maintaining the conventional design of dry storage cask.

2. Experimental Works

In this section, a test facility design methodology was described for evaluating the enhanced heat removal performance of dry storage cask through hybrid heat pipes. To evaluate the heat transfer performance, a dry cask test facility that has 1/5 length scaled down was

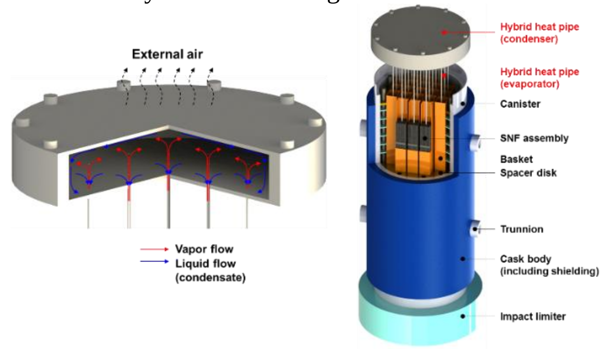


Fig. 1. Nuclear battery concept of UNIST Canister [3]

constructed while maintaining the scaling ratio of the single-phase natural circulation of the internal charged helium gas. The reference model of the dry cask is a dual-purpose metal cask with 10-year cooled 21 PWR SNF developed by KORAD, assuming 1 kW decay heat generation per fuel assembly.

2.1 Scaling Methodology of Experimental Facility

For the design evaluation of UCAN, an experimental device for dry storage cask reduced length to 1/5 scale was constructed. This experimental device follows a scaling method that considers natural convection heat transfer and radiant heat transfer of helium in a dry cask. Ishii and Kataoka's scaling law developed for the scaling down of single-phase natural circulation loop and ANL scaling method for RCCS of VHTR were selected to design the dry storage cask where natural convection and radiation heat transfer of charged helium determine the overall thermal performance of the system. [5, 6].

$$U_o = \left\{ \frac{g\beta\dot{Q}}{\rho C_p A_o} \left[\frac{L_c + \frac{1}{2}L_h}{\sum_i F_i \left(\frac{A_o}{A_i}\right)^2} \right] \right\}^{\frac{1}{3}} \quad (1)$$

$$\sum_i F_i \left(\frac{A_o}{A_i}\right)^2 = 1 \quad (2)$$

$$\Delta T_{oR} = \dot{q}_{oR} \frac{l_{oR}}{u_{oR}} \frac{\delta_{oR}}{d_{oR}} \quad (3)$$

Geometric similarities were satisfied to unity the model-to-prototype ratio, and the same fluid and solid material was used for scaling simplicity. Then, the velocity of fluid, u_{oR}, and temperature ratio, ΔT_{oR}, can be obtained using model-to prototype geometric ratio by expression (1)-(3). Table I shows the scaling ratio derived for dry cask.

Table I: Scaling ratio derived for dry cask

Parameter	Value
Length	$l_{oR} = 0.2000$
Velocity	$u_{oR} = \sqrt{l_{oR}}$
Temperature difference	$\Delta T_{oR} = 1.000$
Convective heat transfer coefficient	$h_R = \sqrt{l_{oR}}$
Total heat input	$Q_R = (l_{oR})^{5/2}$

2.2 Description of Experimental Facility

The decay heat of spent nuclear fuel was simulated using 4 cartridge heaters rod per each fuel assembly that total of 84 cartridge heaters at 21 basket ducts was installed to simulate the 21 kW as a reference SNF decay heat generation. For each basket wall, 3 TCs was installed in the axial direction and 5 TCs was attached near the canister wall in the axial direction to measure the helium temperature of each side. The heat pipe module removes the inert gas, charges the working fluid water, and maintains the external conditions until the normal state is reached. Fig. 2,3 shows the test facility and Table II shows the test matrix for thermal evaluation.

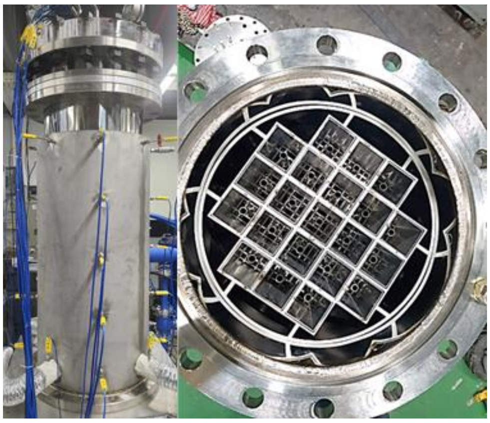


Fig. 2. Photo of 1/5 Scaled down UCAN test facility

Parameter	Value
Heat input(Q)	400-800W
Heat input ratio(Q/Q_{scaled})	1.0-2.0
Helium pressure	1-2atm
Orientation	Vertical
Environment condition	Air (room temperature)
Working fluid	Water
Fill ratio (V_f/V_{evap})	50 -150%
Working Pressure	0.5 – 1 bar
Saturation temperature	81.3 - 100 °C

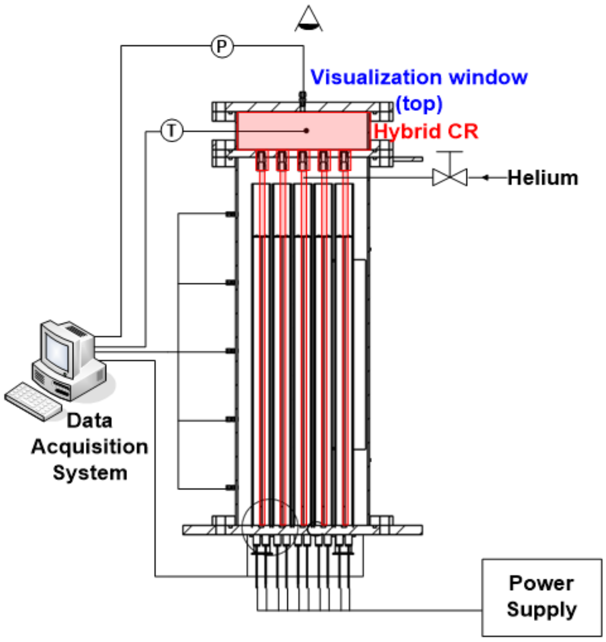
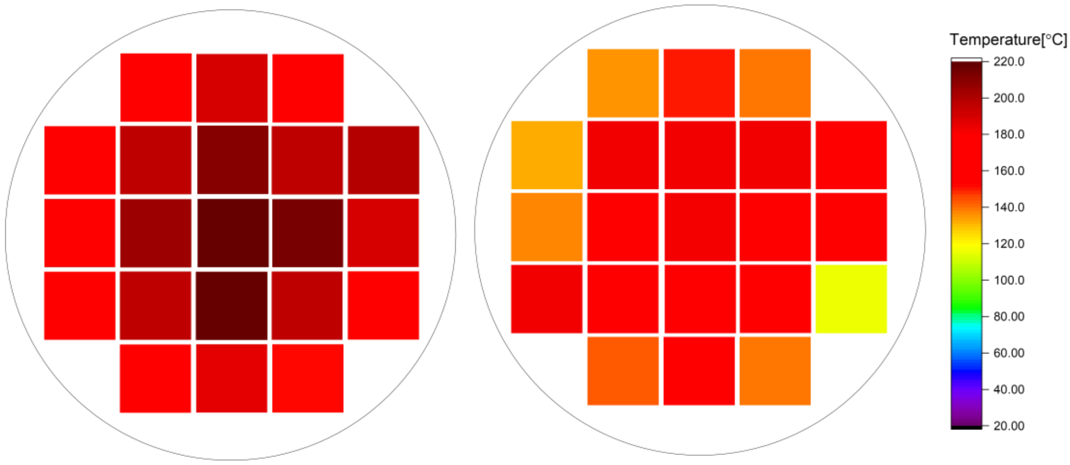


Fig. 3. Schematic of 1/5 Scaled down UCAN test facility.

3. Experimental results and discussion

In this section, charged helium and basket wall temperature distribution under normal conditions of the conventional dry storage cask and UCAN were analyzed quantitatively to confirm the enhanced thermal performance by the design improvement that combined with the hybrid heat pipes. Figure 4 shows the basket wall temperature distribution of 1/5 scaled-down conventional dry cask (a) and UCAN (b). The maximum basket temperature of a conventional heat removal condition of dry cask that natural convection and radiation of helium is the main heat transfer mechanism is 220°C, and the closer it gets to the wall, the lower the temperature. For UCAN, the maximum basket temperature was 150°C and the average temperature difference between the center and near the wall was 40°C due to the operation of the heat pipe. Compared to conventional dry storage cask conditions, the maximum temperature of the basket located in the center of the UCAN was reduced by about 70°C, and the basket at each location was reduced by an average of 60°C. This shows that a hybrid heat pipe is effective in reducing radial temperature gradients and can increase the thermal margin of the dry storage cask.

The axial helium temperature distributions that are a key parameter to evaluate the thermal margin of dry cask were plotted in Fig 5, 6.



(a) Conventional dry cask (b) UCAN

Fig. 4. Temperature distribution of the basket wall (Q=615W, z=0.455m)

Helium continued raising the temperature and rising by buoyancy force until it approached the lid. Similar to the basket wall temperature, design combined with hybrid heat pipe was reduced the axial helium temperature in all locations (Front, Back, Left, Right), which means that additional axial heat removal occurred by hybrid heat pipe not only buoyancy.

The axial temperature gradient reduction due to the hybrid heat pipe control load module can be seen through basket wall temperature plotted in Figs 7 and 8. Similar to sine-shape flux distribution, middle basket temperature has the highest value in dry cask. In UCAN design, overall temperature decrease, especially, the axial temperature gradient decreases significantly due to additional heat removal passes. Reducing the axial and radial temperature gradient of dry storage cask can delay the temperature degradation and ensure system integrity, which means that UCAN can have more storage capacity in the same volume than conventional dry casks design.

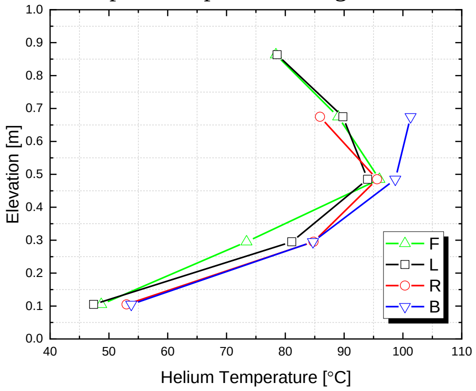


Fig. 5. Helium temperature distributions of general cask

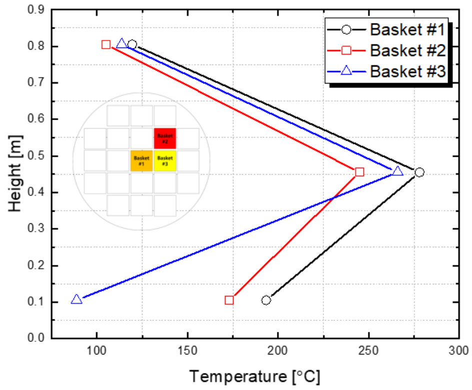


Fig. 7. Axial basket temperature distribution of general cask

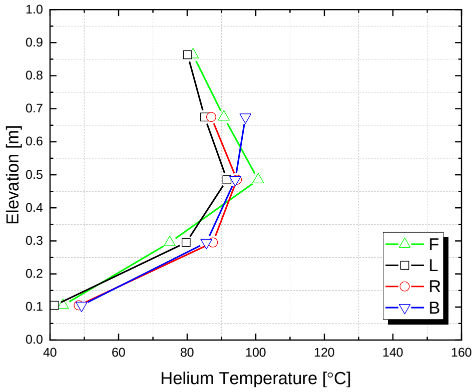


Fig. 6. Helium temperature distributions of UCAN

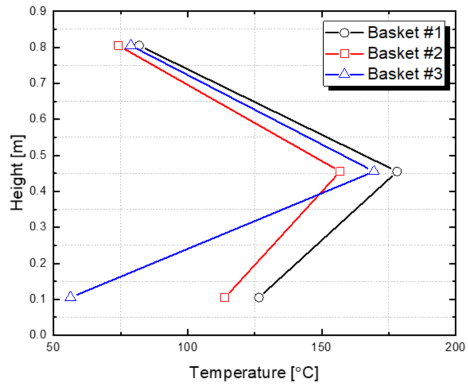


Fig. 8. Axial basket temperature distribution of UCAN

4. Conclusion

To enhance the thermal margin for securing safety and extend the design concept for recycling waste heat like a nuclear battery from conventional dry storage cask using a hybrid heat pipe, UCAN was proposed. 1/5 scaled-down test facility of UCAN was designed based on scaling law to confirm the thermal enhancement performance by a hybrid heat pipe. Through the experimental results, UCAN can secure the additional axial heat path that reduces the maximum and average temperature of the basket wall and helium compared to the conventional dry storage cask. The improved decay heat removal rate and extended temperature margin expected more capacity and safety of system integrity at the same volume. In the future, the thermal performance evaluation of UCAN design under various conditions (steady, off-normal) will be conducted to further investigate safety improvement and electric conversion systems such as Stirling engine and TEG will combine to test the dry storage cask as a nuclear battery.

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