Thermal Management and Electricity Generation Concept of Dry Storage Cask with a Hybrid Heat Pipe for Enhancing Safety of Spent Fuel

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1. Introduction

The thermal management of the spent nuclear fuel generated by nuclear power plants is a major issue in Korea due to the saturation of the wet storage pools. Alternatively, it is considered that the dry storage facility is the one possible solution for long-term cooling of the spent nuclear fuel. Several dry storage casks are currently studying to enhancing the safety, security, and monitoring system. In Korea, a dual-purpose metal cask is suggested and currently developing. To evaluate the critical safety in normal and transient conditions, critical stabilities were conducted using CSAS 6.0 [1,2]. The experimental investigation of heat removal of a concrete storage cask was also conducted [3]. In Japan, two candidates of the dry storage cask were suggested and analyzed the effect on the flow path under normal and accident conditions. The results showed the enhanced cooling performance according to the modification of flow path geometry [4-6]. There are several ideas and patents of the cask, including heat pipe, photovoltaic-cell, thermal electric modules, and Stirling engine for thermal management of the spent nuclear fuel. To enhance the power generation and cooling system was suggested with various heat engines for application of both dry and wet storage systems [7,8]. These concepts were considered for the emergency or auxiliary power supply based on the generated heat [9-11].

To achieve enhanced cooling performance and recycling of waste heat, an advanced dry storage cask concept (UCAN, UNIST CANister) was proposed at the Ulsan National Institute of Science and Technology (UNIST) [10-12]. This concept consists of a hybrid heat pipe combined with a heat pipe heat removal device, Stirling engine, and a DC generator for contributing to roles of both cooling and recycling the spent fuel. In this paper, combined thermal management and electric generation using an integrated cooling and power generation system were analyzed based on the results from a 1/10 scale test facility. To confirm the effect of the integrated system, the heat transfer performance of the dry storage cask for electric generation and its thermal efficiency were investigated. The experimental results gave the temperature distribution, the heat transfer performance of the integrated system, and the generation efficiency under normal operation. These results demonstrate that the UCAN concept can possibly be used to enhance the dry storage cask and generate electricity.

2. Experimental Setup and Procedure

An experimental study has been performed to test the thermal performance and efficiency of the UCAN. The test facility is designed with a 1/10-scale dry storage cask. The capabilities of both enhanced heat removal and electric generation were experimentally confirmed under normal conditions. Each test was conducted at a constant air temperature (20°C) with a constant heat load. Until the temperatures of the overall measurement position reached a stable condition (±0.5 °C/min), the heat load was maintained without any other manual control.

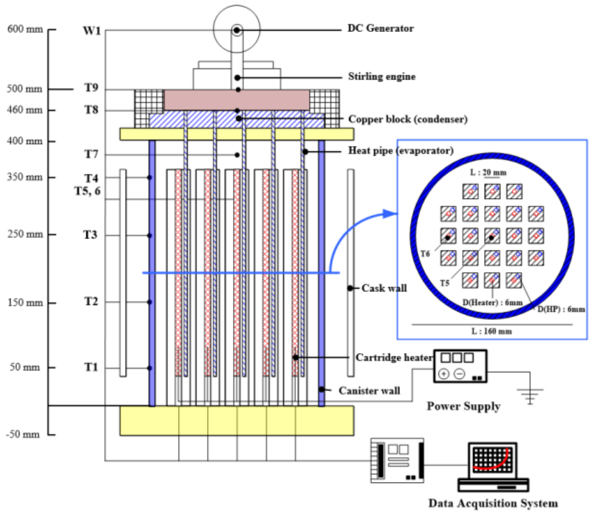


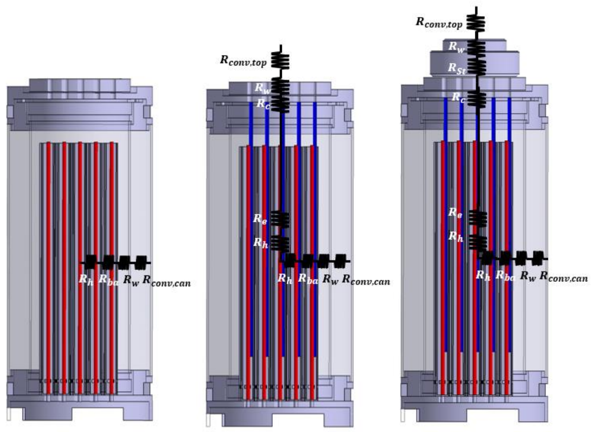
Fig. 1 Schematics of the test facility for UCAN

Table. 1 Test matrix of the UCAN

	UCAN-B	UCAN-HP	UCAN-HS
Power (W)	35	35	35
	45	45	45
	55	55	55
	65	65	65
Heat pipes	0	21	
Stirling engine	0	0	1
Heat transfer	Cask with air flow of canister wall		
	-	Heat pipes	Heat pipes
	-	-	Stirling engine

3. Thermal resistance model

To analyze the experimental results, a thermal resistance network model was used with the previous correlations. Two heat transfer paths were considered in the test facility: the radial heat transfer from the heater to the canister wall and the vertical heat transfer from the heat pipes to the copper block/Stirling engine.



UCAN-B UCAN-HP UCAN-HS

Fig. 2 Schematics of the test facility with thermal resistance network

To remove the heat, radial heat transfer was also used in the case of the conventional dry storage cask. This heat removal path was maintained in the suggested design concept. The combined heat transfer of radiation and convection is a main heat transfer mechanism and the heat goes to the canister wall. The overall resistance of the UCAN was determined by

Table. 2 The previous correlations for thermal resistance network [13-16]

Heater	$h_{rad,h} = \sigma\varepsilon(T_{assem}^2 + T_g^2)(T_{assem} + T_g)$ $h_{conv,h} = 0.515\left(\dfrac{k^4 g\beta(T_s - T_\infty)}{\nu\alpha L}\right)^{1/4}$
Canister surface	$h_{conv,can} = 0.59\left(\dfrac{k^3 g\beta(T_s - T_\infty)}{\nu\alpha}\right)^{1/4}$
Heat pipe	$h_e = 0.32\left(\dfrac{\rho_l^{0.65} k_l^{0.3} C_p^{0.7} g^{0.2} q_e^{0.4}}{\rho_v^{0.25} h_{fg}^{0.4} \mu_l^{0.1}}\right)\left(\dfrac{P_{sat}}{P_{amb}}\right)^{0.3}$ $h_c = 0.925\left(\dfrac{\rho_l^2 k_l^3 g h_{fg}}{q_c A_c \mu_l}\right)$
Stirling engine	$h_{St} = \dfrac{h\,\mathrm{Pr}^{2/3}}{C_p \dot{m} / A_c}$
Upper lid	$h_{conv,top} = 0.54\left(\dfrac{k^4 g\beta(T_s - T_\infty)}{\nu\alpha L}\right)^{1/4}$
Wall	$k_w = \dfrac{t_w}{k_w A_w}$, $k_b = \dfrac{r_b}{k_{eff} A_b}$

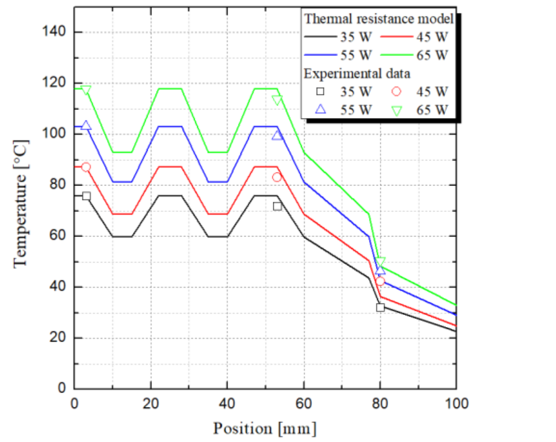
$$\frac{1}{R_o} = \frac{1}{R_{radial}} + \frac{1}{R_{axial}} \quad (1)$$

$$R_{radial} = R_h + R_{ba} + R_w + R_{conv,can}$$
$$= \frac{1}{h_h A_h} + \frac{1}{h_{ba} A_{ba}} + \frac{t_w}{k_w A_w} + \frac{1}{h_{conv,can} A_{conv,can}} \quad (2)$$

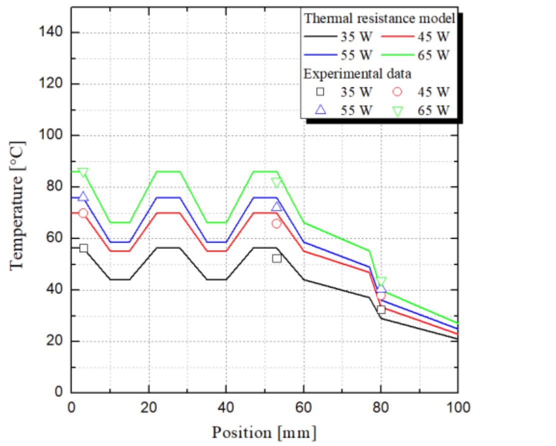
$$R_{axial} = R_h + R_e + R_c + R_{St} + R_w + R_{conv,top}$$
$$= \frac{1}{h_h A_h} + \frac{1}{h_e A_e} + \frac{1}{h_c A_c} + \frac{1}{h_{St} A_{St}} + \frac{t_w}{k_w A_w} + \frac{1}{h_{conv,top} A_{conv,top}} \quad (3)$$

4. Results and discussion

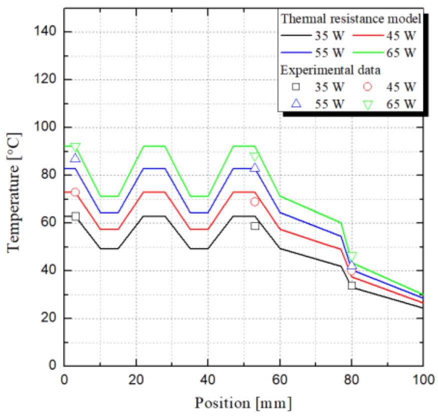
To validate the thermal resistance model, the theoretical results are compared to the experimental data. The radial path consists of several structures: the heater, the basket structure, and canister wall. Therefore, the overall thermal resistance of radial heat transfer is determined by the combined thermal resistances. In case of UCAN-B, the higher temperature of the heater and the wall temperature are calculated in comparison with experimental results, and the results are a good agreement (within 12.2%).



(a) UCAN-B



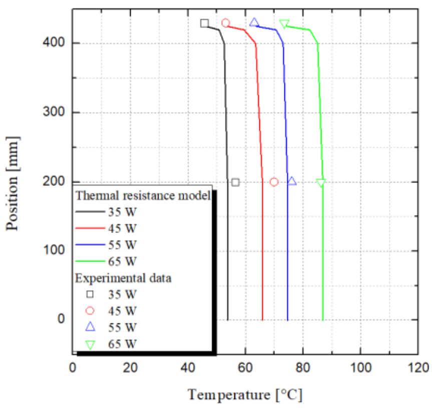
(b) UCAN-HP



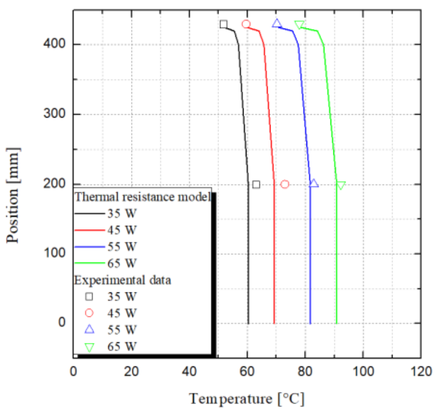
(c) UCAN-HS

Fig. 3 Temperature distribution of the radial heat transfer path

The axial heat transfer path consists of the heater, the heat pipe, the Stirling engine, and the lid wall. The measured temperature is the surface temperatures of the top lid and the evaporator section under the constant heat load. The axial heat transfer is calculated for both UCAN-HP and UCAN-HS inserted heat pipes. The maximum temperature difference of the axial heat transfer path is 6% for the evaporator of the heat pipe.



(a) UCAN-HP



(b) UCAN-HS

Fig. 4 Temperature distribution of the axial heat transfer path with thermal resistance network model

Total thermal resistance decreases according to the increase of the heat input of the heater. UCAN-B has largest thermal resistance among the three cases because of the single heat transfer path and it has a range from 1.30 to 1.52 K/W. The thermal resistances are in the range from 0.90 to 0.96 K/W under the test condition. This trend in total thermal resistance can be explained by the axial heat removal.

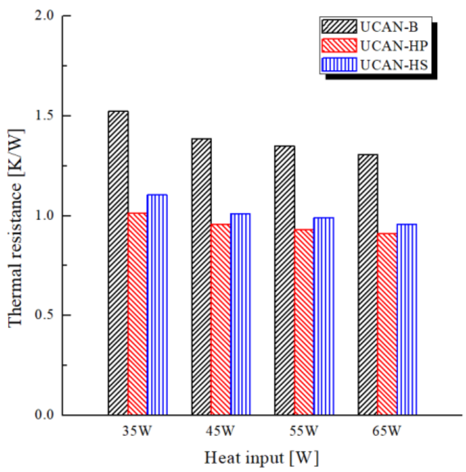


Fig. 5 Total thermal resistance of the UCAN test facility based on thermal resistance network model

Based on the axial and radial thermal resistance, the heat transfer ratio between axial and radial heat transfer is determined. The cooling efficiency is defined as the ratio of the heat removal of the heat pipe to the supplied heat. The cooling efficiencies decrease slightly with the increase of the heat load. The heat pipes are located inside the assemblies of the heater; therefore, axial heat transfer is preferentially conducted. The cooling efficiency of the low heat load is higher than those of high heat loads under the test conditions.

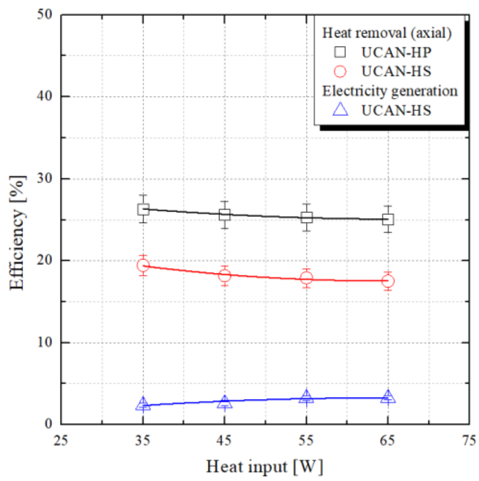


Fig. 6 Cooling and electricity generation efficiency of the UCAN systems according to the heat input

The previous results of the low and moderate temperature Stirling engine with tested results are collected and are shown in Fig. 7. The temperature differences of the tested results range from 53.0 °C to 82.2 °C in the scaled test facility and it has a proper trendline comparable to that in previous studies.

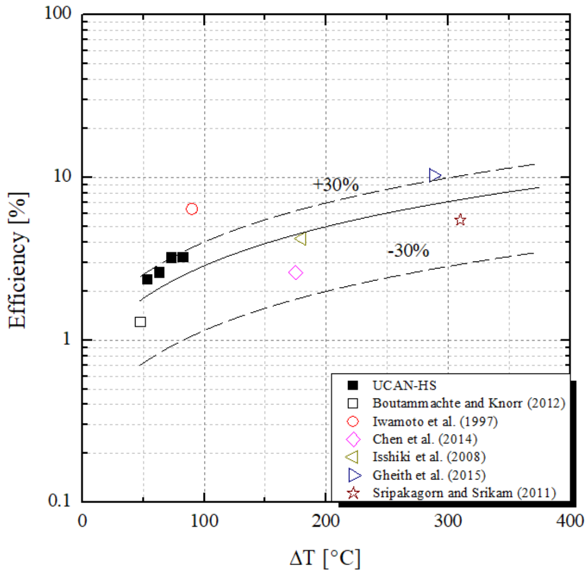


Fig. 7 Experimental results of Stirling engines with previous studies under the low and moderate temperature Stirling engines

5. Conclusions

To achieve enhancement of cooling performance and the recycling of waste heat, an advanced dry storage cask concept (UCAN) was proposed. This concept consists of a hybrid heat pipe combined with a heat pipe heat removal device, Stirling engine, and DC generator for contributing to roles of both cooling and recycling the spent fuel. A comparison study among a conventional dry storage cask, a cask with a heat pipe, and a cask with a heat pipe and a Stirling engine was quantitatively evaluated and validation of the thermal resistance network model was conducted by using the experimental results. The cooling efficiencies of UCAN-HP and UCAN-HS range from 25.0% to 26.3% and from 17.5% to 19.4%, respectively. For UCAN-HS, the efficiency of electricity generation ranged from 2.4% to 3.3%. Therefore, the results demonstrate the feasibility of enhancing heat removal performance of the dry storage cask and electricity generation by using SNF. The generated heat can be used for the emergency cooling or auxiliary power system; therefore, it is possible to contribute to safety of the dry storage cask.

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