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Combined Thermal Management and Power Generation Concept for the Spent Fuel Dry Storage Cask

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1. Introduction

The current strategy for management of the spent fuel remained the spent fuel pool for high power density of spent fuel and dry storage cask for those of low power density. The management of the spent nuclear fuel generated by nuclear power plants is a major issue in Korea due to insufficient capacity of the wet storage pools. Therefore, it is considered that dry storage system is the one possible solution for storing spent fuel. A dual-purpose metal cask (transportation and storage) is currently developing in Korea. This cask has 21 of fuel assemblies and 16.8 kW of maximum decay heat. To evaluate the critical safety in normal/off normal and accident conditions, critical stabilities were conducted by using CSAS 6.0 [1,2]. The experimental investigation of heat removal of a concrete storage cask was also conducted under normal, off normal and accident conditions [3]. The results of the evaluation showed a good safety of the dry storage cask. However, the issues of the enhancement of thermal performance still remained. 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 thermal performance according to modification of flow rate [4-6].

To achieve the enhancement of cooling performance and the recycle of waste heat, an advanced dry storage cask (UCAN, UNIST canister) was proposed at the Ulsan National Institute of Science and Technology (UNIST) [7]. Its system consists the hybrid control rod combined with heat pipe, Stirling engine, and DC generator for contributing the both rule of cooling and recycling the spent fuel. Hybrid control rods consist the metal cladding, working fluid, and a neutron absorber (B_4C) and it is located at the center of each fuel assembly. The decay heat is transported from spent fuel to the top of the cask by the phase change of the working fluid. Stirling engine can operate by using the temperature difference between the upper dry cask and air.

In this paper, combined thermal management and power generation concept using integrated cooling and generation system was analyzed based on the experimental test. The results showed the temperature distribution of the wall and inside of the dry cask at the normal condition. In the experimental test, the thermal performance and electric generation were determined for confirming the effect of the integrated cooling and generation system. Results show that the concept of UCAN can be possible to enhance the thermal performance and generate the electricity from the dry storage cask.

2. Experimental Setup and Procedure

To verify the concept of the advanced design, a new type of test facility for dry storage cask was designed in 1/10 scale of concrete dry storage cask. Fig. 1 shows the schematics of the test section and visualization.

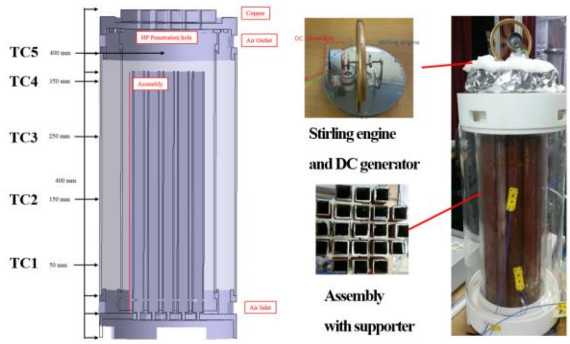

Fig. 1 Schematics of the test section and visualization

The capabilities both enhanced heat removal and electric generation were experimentally confirmed under normal conditions. Table. 1 shows the test matrix of the small scaled test facility.

Table. 1 Test matrix of small scaled test facility

	Case 1	Case 2	Case 3
Power (#/16.8 kW)	2/1000 – 4/1000	2/1000 – 4/1000	2/1000 – 4/1000
Heat pipes	-	5	
Geometry	Cask with air flow of canister wall	Cask with air flow of canister wall; Heat pipe	Cask with air flow of canister wall; Heat pipe; Power generation system (Stirling engine, DC generator)
Conditions	Normal condition with constant power		

Case 2 is the cask with heat pipe cooling devices that have an additional cooling path from cartridge heater (core) to the copper block (condenser, air cooling). The geometry of the case 3 is similar with those of the case 2 and power generation system is located on the copper block. Ambient temperature is maintained at 18-20 °C.

3. Theoretical Method

In the experimental test, heat input supplied by the cartridge heater and working fluid vapor of the heat pipe rises through the evaporator to the condenser. The electricity efficiency is assumed as 0.99.

$$\dot{Q}_{heater} = \frac{\dot{W}_{electric}}{\eta_{electric}} \quad (1)$$

The ultimate heat sink is the air and condenser of the heat pipe is cooled by the natural convection on the horizontal flat copper block.

$$Ra = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu\alpha} \quad (2)$$

The heat removal of the condenser is determined by

$$\dot{Q}_{HP} = hA_s(T_s - T_\infty) \quad (3)$$

$$Nu = 0.54Ra^{1/4} \quad (4)$$

The general cost and annular capital cost balance of the steady state can be determined by

$$\dot{C}_{in} + \dot{Z}_{tot} = \dot{C}_{out} \quad (5)$$

$$\dot{Z}_{tot} = \dot{Z}_{Ci} + \dot{Z}_M = \frac{\Omega[AC]}{\tau} \quad (6)$$

Where $\dot{C}_{in}$ is the total cost rate of the input, $\dot{C}_{out}$ is the cost rate of the output, $\dot{Z}_{tot}$ is the total capital cost rate of the equipment, $\dot{Z}_{Ci}$ is the cost rate of the investment, $\dot{Z}_M$ is the maintenance cost, [AC] is the annual capital cost, τ is the working hour [8].

3. Results and Discussion

To analyze the effect of the heat pipes, the temperatures of the canister wall and inside air were measured according to the heat load. The wall temperature decreased with the increase of the heat load. The air temperature inside canister was dramatically decreased due to the heat removal to heat pipes.

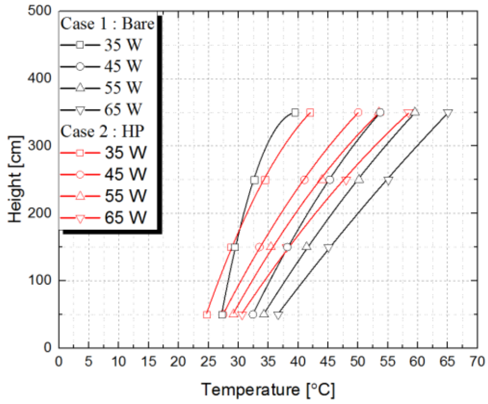

Fig. 2 Temperature distribution of the canister wall

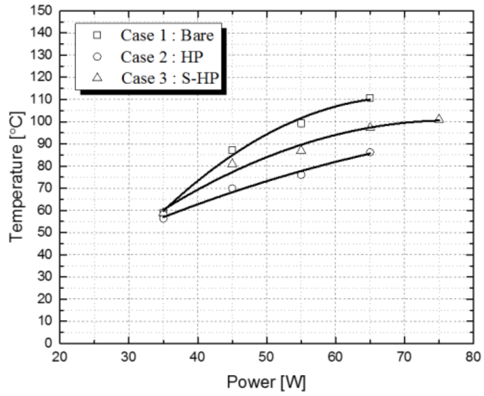

Fig. 3 Air temperature (inside)

The working temperature of the heat pipe is shown in Fig. 4. The operation temperature both Case 2 and Case 3 was increased due to the increase of the air temperature inside the canister. The operation temperature of Case 3 has slightly lower than those of the Case 2 due to effect of additional thermal resistance layer (Stirling engine on the copper block). Table. 2 shows the summary of the experimental results.

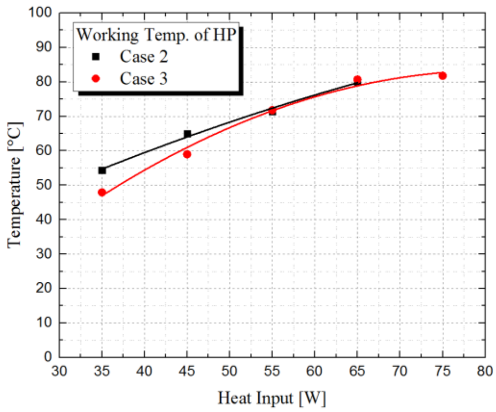

Fig. 4 Operation temperature of the heat pipe

Table. 2 Summary of the experimental results

	Power [W]	Max. Temp [ºC]	Ra [-]	Nu [-]	h [W/m^{2}K]	Heat removal (HP) [W]	η_{HP} [%]	η_{total} [%]	Cost rate [won/h]
Heat pipe	35	54.37	1.559*10^7	33.93	5.56	5.60	16.0	-	-
	45	64.95	1.978*10^7	36.01	5.90	7.55	16.7	-	-
	55	71.43	2.234*10^7	37.13	6.08	8.79	15.9	-	-
	65	80.07	2.577*10^7	38.47	6.30	10.51	16.1	-	-
Heat pipe with stirling engine	35	47.92	1.304*10^7	32.45	5.32	4.48	12.8	2.375	0.009765
	45	58.98	1.742*10^7	34.88	5.72	6.44	14.3	2.615	0.012974
	55	71.76	2.248*10^7	37.18	6.09	8.86	16.1	3.240	0.026598
	65	80.69	2.602*10^7	38.57	6.32	10.63	16.3	3.247	0.032039

*Electricity cost : 93 KRW/kWh

The efficiency of the Stirling engine was the range of 2.375 to 3.247% in the experimental test, shown in Fig. 5. According to the increase of the heat load, the efficiency was increased. The maximum efficiency and cost rate were determined at 65W. The output electric power and cast rate are shown in Fig. 6 The cost rate is 85 to 290 KRW/year in 1/10 scale dry cask and this system has low efficiency and cost rate due to low heat load condition (approximately 2/1000 to 4/1000 of full-scale dry cask). It shows the possibility of combined cooling and power generation. To achieve high-cost rate, the large-scale test facility and optimization of the power generation system are needed.

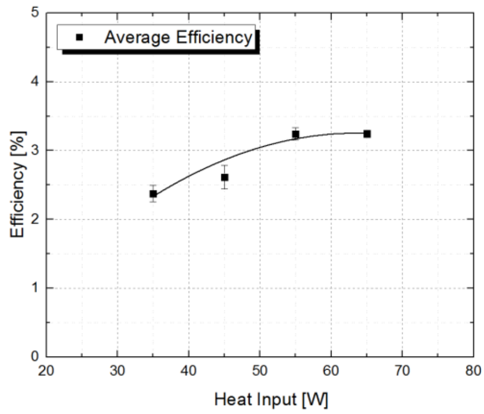

Fig. 5 Efficiency of the Stirling engine with heat pipes

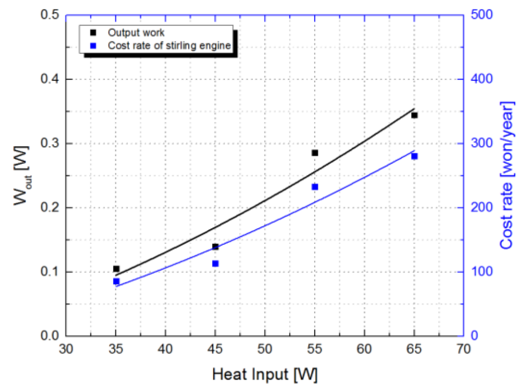

Fig. 6 Output electric power and cost rate

4. Conclusions

To verify combined thermal management and power generation concept, a new type of test facility for dry storage cask was designed in 1/10 scale of concrete dry storage cask. The experimental study involved the cooling methods that are an integrated system on the top of the dry cask and air flow path on the canister wall. The results showed the temperature distribution of the wall and inside of the dry cask at the normal condition. The influence of the change of the heat load and cooling system were investigated. The heat removal by the integrated system is approximately 20% of the total heat removal of the dry cask with reduced wall temperature. In these tests, economic analysis is conducted by applying the concept of the cost and efficiency. Under different decay power cases, the energy efficiency of the heat pipe and Stirling engine are determined and compared based on experimental results. The average efficiencies of the Stirling engine were the range of 2.375 to 3.247% under the power range of 35–65W. These results showed that advanced dry storage concept had a better cooling performance in comparison with present cask design and a feasibility of the integrated cooling and power system for dry storage cask.

The future works are focused on the enhancement of the power efficiency and design of the realistic dry storage cask. The final target of the combined thermal management and power generation concept is to the development of the co-generation system with renewable energies.

ACKNOWLEDGEMENTS

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