Transactions of the Korean Nuclear Society Virtual Autumn Meeting
December 17-18

Decay Heat Removal Characteristics of Full-Scale Hybrid Control Rod-Heat Pipe for Advanced Spent Fuel Dry Storage Cask Design

Kyung Mo Kim, In Cheol Bang *
Department of Nuclear Engineering,
Ulsan National Institute of Science and Technology (UNIST),
50 UNIST-gil, Ulju-gun, Ulsan 44919
*Corresponding author: icbang@unist.ac.kr

1. Introduction

Spent fuel wet storage capacity of in on-site nuclear power plant has been saturated with delay of final disposal facility plan and decommissioning plan of NPPs. Until the determination and construction of repossessing or disposal facility, the spent fuel cooled at wet storage facility would be transferred to interim storage facility and managed. Spent fuel dry storage casks, representative of interim storage facility, are under construction and management satisfying safety criteria in terms of shielding, sealing, structural integrity, and neutronics. However, wall thickness, semi-insulation layer (shielding part), and narrow flow channel of the cask designs satisfying various safety criteria restricts decay heat removal efficiency and volumetric storage capacity. As an advanced cask design having improved decay heat management performance, UNIST CANister (UCAN) [1].

Main novelty of UCAN design is installation of the hybrid control rod-heat pipe, which is a specialized device combining the function of thermosyphon heat pipe and control rod as demonstrated in Fig. 1. Through the neutron absorption with boron carbide pellet and axial decay heat removal with convective phase change of working fluid of the hybrid control-rod heat pipe, decay heat removal capacity could be enhanced with maintaining the subcriticality.

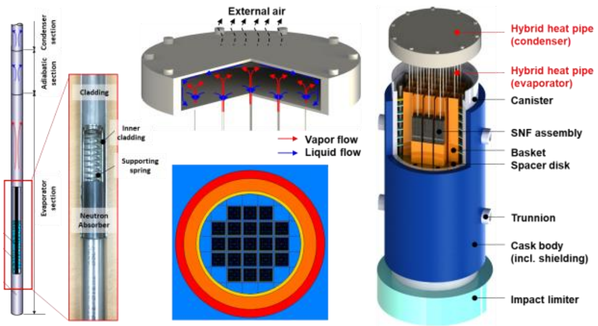

Fig. 1. Photo of 1/5 Scaled UCAN test facility [1]

For the development of UCAN with demonstration of its cooling performance and safety analyses under various operating conditions, thermal-hydraulic behavior inside the hybrid control rod-heat pipe must be clarified. The phase change and convection of working fluid (two-phase flow) inside the hybrid control rod-heat pipe under sub-atmospheric pressure condition have not been studied. Conventionally, fill ratio (FR) of working fluid and operating pressure of thermosyphon heat pipe dominate its cooling performance. Therefore, thermal-hydraulic characteristics of the hybrid control rod-heat pipe according to fill ratio and internal pressure were observed by series of experiments. In addition, effect of integration of the hybrid control rod-heat pipe on thermal safety of dry storage cask was comprehensively quantified.

2. Experimental Setup

Test facility simulating a 1/4-single fuel assembly with 6m-full height was constructed as shown in Fig. 2 to observe the thermal behavior of UCAN design and analyze thermal-hydraulic behaviors of the hybrid control rod-heat pipe.

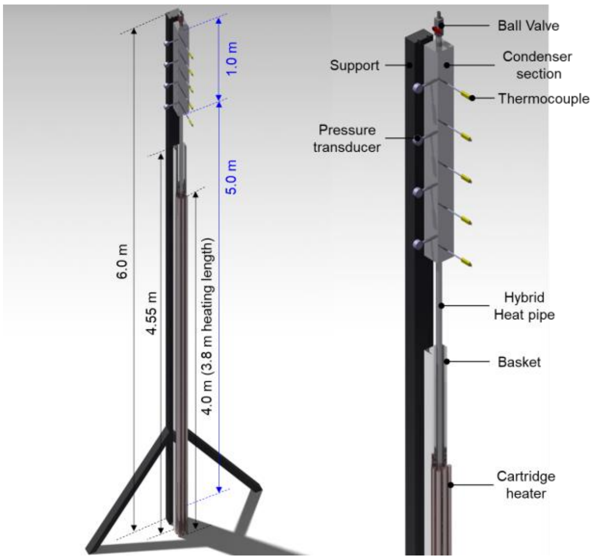

Fig. 2. Photo of 1/5 Scaled UCAN test facility [2]

Guide tube, hybrid control rod-heat pipe, and cartridge heaters were surrounded by 4 m-height square duct (100.0 mm x 100.0 mm, and 3.2 mm thickness). Twelve cartridge heaters having 19 mm outer diameters and 4.0 m length (3.8 m heating length) simulated the spent fuel rods. Power capacity of the heaters was determined by scaling the specific power of the reference assembly. Cross-sectional area of the subchannel was preserved with prototype. A guide tube of 25.4 mm outer diameter (1.7 mm thickness) was located at the center of basket. Stainless steel 316L tube with 19.05 mm outer diameter and 18 mm inner diameter located at the center of guide tube acts as the hybrid control rod-heat pipe. Length ratio of evaporator, adiabatic, and condenser section of the hybrid heat pipe was 4.0 m: 1.0 m: 1.0 m, corresponding to length ratio of spent fuel assembly, upper plenum of cask, and cask lid [2]. An alumina pellet having 17.7 mm outer diameter and 4 m height was integrated at the center of the hybrid control-heat pipe to simulate neutron absorber. Water was charged as working fluid. Twelve K-type thermocouples and five T-type thermocouples measured the wall temperature of the hybrid control rod-heat pipe. Pressure transducer at the top of the hybrid control rod-heat pipe measures the internal pressure. Individual heater temperatures were recorded by embedded K-type thermocouples.

Test matrix for observation of thermal performance of the hybrid control rod-heat pipe is presented in Table I. Thermal-hydraulic parameters, such as density ratio between vapor and liquid of working fluid, latent heat, surface tension, and amount of non-condensable gas, determines heat transfer characteristics of the thermosyphon heat pipe. Therefore, the filling ratio of working fluid and initial pressure of the test section were varied to find the optimal operating condition maximizing thermal management capacity. The single PWR spent fuel assembly with a 55,000 MWD/MTU burn-up and 7-year cooling time [3] is standard of heat load of the facility.

Table I Test range of 1/5 scaled UCAN facility

Parameter	Value
Heat input [W]	450
Internal pressure [bar]	0.3, 0.4, 0.6, 1.0
Fill ratio [%]	30.0, 50.0, 70.0, 100.0
Atmosphere temperature [K]	293.15

3. Results and Discussion

3.1 Temperature Evolutions

Wall temperature evolutions of guide tube (bare; without hybrid control rod-heat pipe) and hybrid control rod-heat pipe (UCAN design; with hybrid control rod-heat pipe operating at 0.3 bar and 30 % FR) were compared as shown in Fig. 3. EVT01~EVT06 are thermocouple locations in axial direction installed at the wall of guide tube corresponding to evaporator section, ADT01 and ADT02 are TCs at adiabatic section, and CNT01~CNT05 are TCs at cask lid.

Guide tube temperature increased as the elevation increased due to buoyancy of air inside the basket. Above heating length of the cartridge heater (4 m), wall temperature was dramatically decreased owing to absence of heat source. The insufficient momentum of helium buoyancy inside the guide tube resulted in nearly equal cask temperature with atmosphere. The guide tube temperature evolution of bare design indicates the decay heat removal by conduction and radiation of helium gas in radial direction.

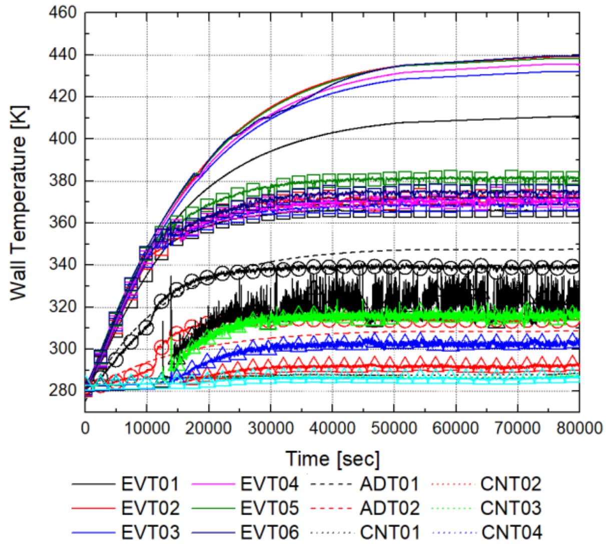

Fig. 3. Basket wall temperature distribution of 1/5 scaled UCAN at steady state (Q=1050 W, z=0.455 m).

The lines with hollow symbols in the graph indicate temperature evolutions of guide tube of UCAN design. As shown in Fig. 3, the temperature increase rates of UCAN design was lower than bare design. Especially, EVT06 (top of evaporator section) temperature was lower than EVT05, owing to return of condensed liquid to evaporator section indicating the phase change and convection of working fluid inside the hybrid control rod-heat pipe. The sudden temperature increases of the adiabatic section around 10,000 sec from start-up of experiment supports the phase change heat transfer accompanying volume expansion of working fluid inside the test section. It is evident with temperature increases at cask lid (condenser section). In addition, the effect of installation of hybrid control rod-heat pipe is also confirmed by heater cladding temperature evolution. The temperature increase rate of heaters in bare design was higher than those of UCAN design. While the heater temperatures of bare design were almost same with guide tube temperature at steady state due to thermal equilibrium, the heater temperatures of UCAN design were higher than guide tube temperature.

3.2 Temperature Distributions

The heat transfer capacity of the hybrid control rod-heat pipe dominantly affects the temperatures of cask structures. To quantify the effect of heat removals through hybrid control rod-heat pipe with various operating conditions on thermal behavior of cask, axial temperature distributions of heater cladding and guide tube were compared as shown in Fig. 4. UCAN design showed lower guide tube and heater cladding temperatures compared to conventional cask design.

The guide tube temperatures of adiabatic section of UCAN design exhibited higher temperature distribution than bare design. The axial direction through the hybrid control rod-heat pipe resulted in reduced temperature at heating section and increased temperature at non-heating section. In addition, the reduction of structural temperature was varied with fill ratios and operating pressures of the test sections. The maximum temperatures of heater cladding and guide tubes at steady states were summarized in Table II. The maximum reduction of guide tube and heater cladding temperatures were 78 K and 42 K, respectively, at the test section operating with fill ratio and operating conditions of 0.3 bar and 50 % FR.

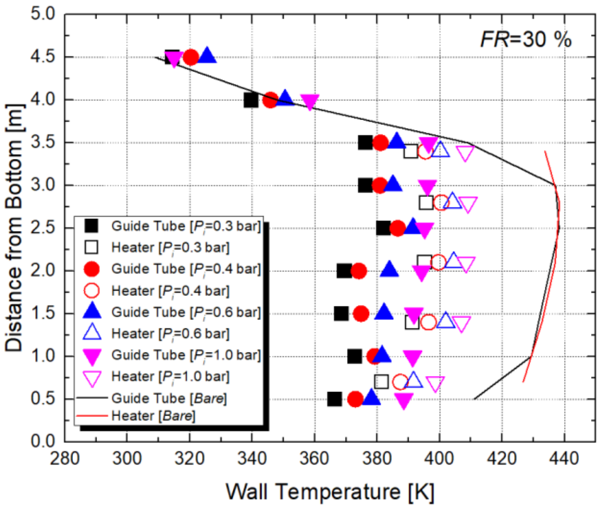

Fig. 4. Comparison of guide tube and heater temperatures according to cask design and operation conditions of the hybrid control rod-heat pipe.

Table II Guide tube and heater temperatures at steady states

Parameter		Heater [K]	Guide Tube [K]
Bare		438.0	437.0
UCAN			
FR [%]	Pint [bar]	Heater [K]	Guide Tube [K]
30.0	0.3	395.7	382.0
	0.4	400.5	386.6
	0.6	404.5	391.5
	1.0	409.1	396.4
50.0	0.3	391.6	379.0
	0.4	395.9	378.3
	0.6	401.1	387.7
	1.0	408.6	396.7
70.0	0.3	394.9	377.4
	0.4	397.2	382.6
	0.6	401.3	389.2
	1.0	410.4	393.0
100.0	0.3	393.2	379.5
	0.4	396.8	383.6
	0.6	401.8	389.1
	1.0	408.4	397.0

3.3 Heat Removal Characteristics of Hybrid Control Rod-Heat Pipe

For detail analysis on heat transfer performances of the hybrid control rod-heat pipe according to operating conditions, the heat removal rates were calculated based on the measured temperature data and heat balance equations.

The calculated heat removal rates of the hybrid control rod-heat pipe were plotted in Fig. 5. The heat removal rates varied from 60 W to 152 W (13.3 % to 33.8 % of heat input). As the internal pressure increased in constant fill ratio conditions, heat removal rate was decreased, because non-condensable gas at the condenser section impedes the diffusion of steam to cask lid wall, and accumulated non-condensable gas at the top of the cask lid reduced effective heat transfer length. Additionally, increased saturation temperature of working fluid resulted in higher structural temperatures at steady states. While there was inversely proportional relationship between internal pressure and heat transfer performance, the decay heat removal capacity according to the fill ratio was unclear. To clarify the heat removal behavior of the hybrid control rod-heat pipe according to fill ratio conditions, hydraulic phenomena was analyzed profoundly.

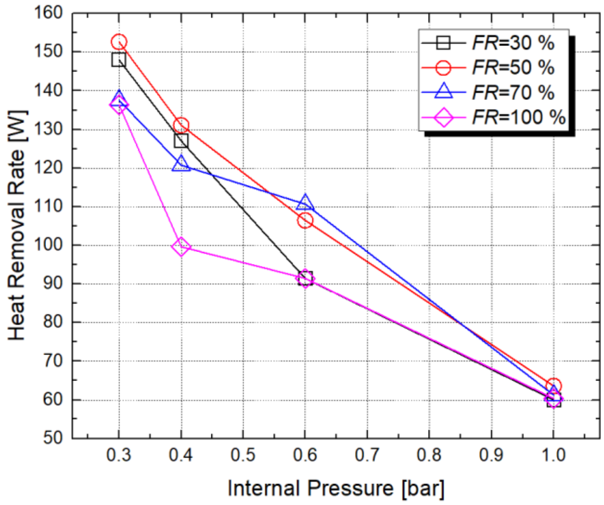

Fig. 5. Heat transfer rates of the hybrid control rod-heat pipe according to internal pressures and fill ratios.

The representative variation of condenser temperature was depicted in Fig. 6. The wall temperature oscillations were observed for all fill ratio conditions. The oscillation periods were from tens of seconds to hundreds of seconds. The wall temperature oscillation with long term period has been frequently reported by thermosyphon operating at sub-atmospheric pressure [4-8]. Due to large density ratio between liquid and vapor in sub-atmospheric pressure, bubble size remarkably expands compared to atmospheric pressure condition. The large-size bubble in a confined channel such as thermosyphon becomes slug. After the vapor slug pushes the liquid plug and reaches the condenser section. Finally, vapor slug collapses and the liquid returns to evaporator section along the wall by gravity. Repetition of prementioned phenomena is called geyser or intermittent boiling. Through the analysis on wall temperature behavior, it was confirmed that main heat transfer mechanism of the hybrid control rod-heat pipe is geyser boiling. In addition, the geyser periods are dependent on fill ratio of the test section. For the quantification of fill ratio and internal pressure effect on geyser period and heat transfer behavior, further analyses will be conducted.

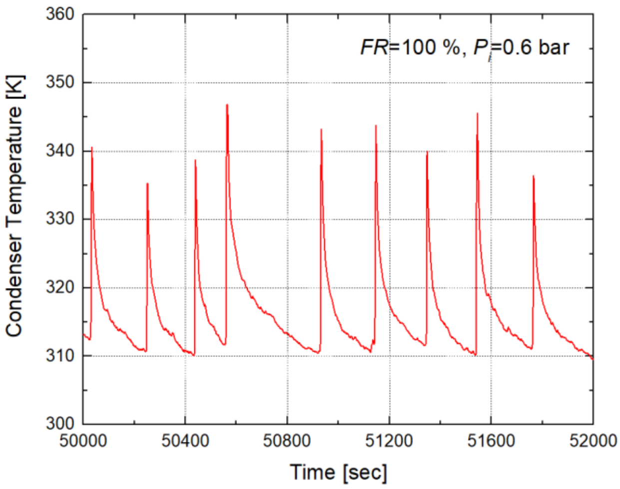

Fig. 6. Wall temperature variation at condenser section of the test section (100 % FR and 0.6 bar internal pressure).

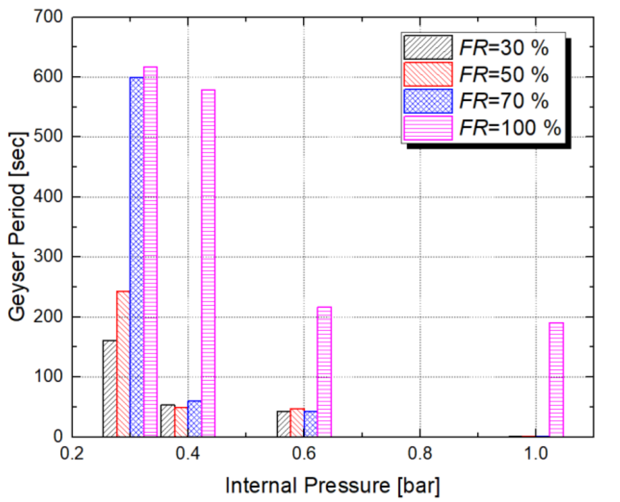

Fig. 7. Geyser boiling periods according to operating conditions of the hybrid control rod-heat pipe.

4. Conclusions

Advanced spent fuel dry storage cask design, UCAN based on hybrid control rod-heat pipe, was suggested for improved decay heat removal performance. In this study, the performance of thermal management of UCAN design was observed by experimental facility simulating a full-scale single spent fuel assembly. The experimental data demonstrated that the hybrid control rod-heat pipe could reduce structural temperatures (maximally 78 K for guide tube temperature) efficiently with improved thermal capacity from 13.3 % to 33.8 %.

Heat removal rate of the hybrid control rod-heat pipe was varied with fill ratios and internal pressures. The heat removal performance was inversely proportional to internal pressure due to non-condensable gas effect. In addition, geyser boiling accompanying long waiting time for bubble generation was deduced as main phenomenon inside the hybrid control rod-heat pipe and it dominated heat removal capacity. Through further analysis on geyser boiling behaviors with operating pressure and fill ratio conditions, the heat removal characteristics of the hybrid control rod-heat pipe will be quantified for the clarification of its performance and development of precise model predicting thermal-hydraulic characteristics.

ACKNOWLEDGEMENTS

This work was supported mainly by Korea Hydro & Nuclear Power Company through the project “Nuclear Innovation Center for Haeorum Alliance” and partly by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20194030202400).

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