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Performance Evaluation of the Concept of Hybrid Heat Pipe as Passive In-core Cooling Systems for Advanced Nuclear Power Plant

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1. Introduction

On March 2011, large scale of earthquake with magnitude 9.0 and tsunami had caused severe core damage of the nuclear reactor in Fukushima, Japan. It showed the vulnerability of the cooling ability of the current nuclear power plant at station blackout (SBO) accident and its extension conditions. Heat pipe is the totally passive cooling device that widely used for heat removal of the variety of applications like electronic devices and CPU [1]. From the unique features of heat pipe, its applications have continuously researched about waste heat management in nuclear energy field for developing passive cooling system.

Singh et al. suggested heat pipe cooling method as emergency core cooling system for spent nuclear fuel pool in containment of nuclear power plant [2]. Mochizuki et al. suggested the loop type heat pipe cooling system for boiling water reactor as a decay heat removal system [3]. Syiridenko researched the passive emergency core cooling system using heat pipes in WWER [4]. Nam et al. suggested the multi-pod heat pipe cooling system to prevent over-pressurization of containment building [5]. Many researches were done for developing passive cooling for nuclear power plant using heat pipe. However, most of them should change existing designs of nuclear power plant, which can affect the integrity of the facilities. As an arising issue for inherent safety of nuclear power plant, the concept of hybrid heat pipe as passive in-core cooling systems was introduced.

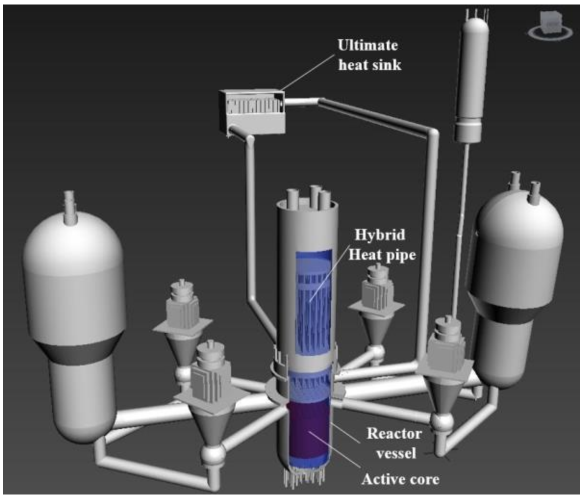


Fig. 1 Systematic design of hybrid heat pipe

Hybrid heat pipe has unique features that it is inserted in core directly to remove decay heat from nuclear fuel without any changes of structures of existing facilities of nuclear power plant, substituting conventional control rod. Hybrid heat pipe consists of metal cladding, working fluid, wick structure, and neutron absorber. Same with working principle of the heat pipe, heat is transported by phase change of working fluid inside metal cask [6]. Figure 1 shows the systematic design of the hybrid heat pipe cooling system.

In this study, the concept of a hybrid heat pipe was introduced as a Passive IN-core Cooling Systems (PINCs) and demonstrated for internal design features of heat pipe containing neutron absorber. Using a commercial CFD code, single hybrid heat pipe model was analyzed to evaluate thermal performance in designated operating condition. Also, 1-dimensional reactor transient analysis was done by calculating temperature change of the coolant inside reactor pressure vessel using MATLAB.

2. Evaluation Method

To evaluate the thermal performance of the hybrid heat pipe with unique design features and cooling performance in the reactor, two-step numerical analysis was done. One is the single hybrid heat pipe simulation with commercial CFD code, ANSYS-CFX, and the other is the one-dimensional thermal hydraulic reactor transient analysis by calculating the coolant temperature inside reactor pressure vessel using MATLAB.

2.1 Analysis methods

Physical domains of the single hybrid heat pipe simulation consist of solid region for metal cladding and neutron absorber structure, porous region for wick structure, and fluid region for vapor path and wick structure. Figure 2 shows the physical domain of single hybrid heat pipe simulation.

Since the heat transfer characteristics of hybrid heat pipe is important in this study, detailed behavior of bubble and condensed liquid droplet was neglected. However, phase change of working fluid at the liquid-vapor interface was considered as a source term in the momentum and energy equation. From that, following assumptions were considered for hybrid heat pipe simulation to solve continuity, momentum and energy equations for heat pipe simulation [7, 8].

1) Incompressible laminar flow for both liquid and vapor
2) Vapor region for vapor path and liquid region for wick structure are separated, and mass and energy transfers occur only at the liquid-vapor interface.
3) All vapor and liquid are considered to be saturated, and properties of liquid and vapor are constant.

2.2 Governing equations

For the single hybrid heat pipe simulation, 3-dimensional steady state continuity, momentum, and energy equations were solved for solid, vapor and liquid regions. For the wick structure, Darcy's law was used to govern momentum equation for liquid flow in porous media with porosity and permeability as momentum loss term. To consider the effect of the latent heat from phase change, mass source, sink and energy source, sink terms were added to the evaporator and condenser region. For vapor region, the continuity, momentum, and energy equations can be written as follows [9]:

$$\nabla \cdot (\rho \mathbf{U}) = 0 \quad (1)$$

$$\nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) = -\nabla p + \nabla \cdot \left(\nabla \mathbf{U} + (\nabla \mathbf{U})^T - \frac{2}{3} \delta \nabla \cdot \mathbf{U} \right) \quad (2)$$

$$\nabla \cdot (\rho \mathbf{U} h) = \nabla \cdot \left(k \nabla T \right) + \nabla \mathbf{U} + S_E \quad (3)$$

The radial vapor velocity boundary conditions were considered for mass change from evaporation and condensation at the vapor-liquid interfaces given by [10]:

$$v_e = +\frac{q}{2\pi r_{int} L_e \rho_v h_{fg}} \quad (4)$$

$$v_a = 0 \quad (5)$$

$$v_c = -\frac{q}{2\pi r_{int} L_c \rho_v h_{fg}} \quad (6)$$

The temperature of vapor-liquid interface for all sections was calculated by Clausius-Clapeyron formula [11]:

$$T_{int} = \frac{1}{\dfrac{1}{T_{sat}} - \dfrac{R}{h_{fg}} \ln\left(\dfrac{P_v}{P_{v,sat}} \right)} \quad (7)$$

In the wick region, Darcy's law inside porous media was considered.

$$\nabla \cdot (\rho (\mathrm{K} \cdot \mathbf{U} \otimes \mathbf{U}) - \nabla \cdot \left(\mu_e K \cdot (\nabla \mathbf{U} + (\nabla \mathbf{U})^T - \frac{2}{3} \delta \nabla \cdot \mathbf{U} \right) = \varepsilon S_M - \varepsilon \nabla p \quad (8)$$

For modeling phase change phenomenon, source and sink terms were added at the wick in evaporator and condenser regions.

$$S_e = -\frac{q}{\pi \left((r_{int} + t)^2 - r_{int}^{\ 2} \right) L_e} \quad (9)$$

$$S_c = +\frac{q}{\pi \left((r_{int} + t)^2 - r_{int}^{\ 2} \right) L_c} \quad (10)$$

For the reactor transient analysis, MATLAB script was written to calculate the temperature change of coolant inside reactor pressure vessel. With integrating the equation with respect to time, final temperature of coolant was found. Coolant temperature was calculated as:

$$MC_{p,l}(T_f - T_{bulk}) = \int_0^{t_f} P(t)dt - \int_0^{t_f} Q_{HP} dt \quad (11)$$

Overall thermal resistance can be obtained from total amount of heat removed through hybrid heat pipe from the result of single hybrid heat pipe simulation. Total amount of heat removed by hybrid heat pipe can be expressed as follows:

$$Q_{HP} = \frac{T_f - T_c}{R_{total}} \quad (12)$$

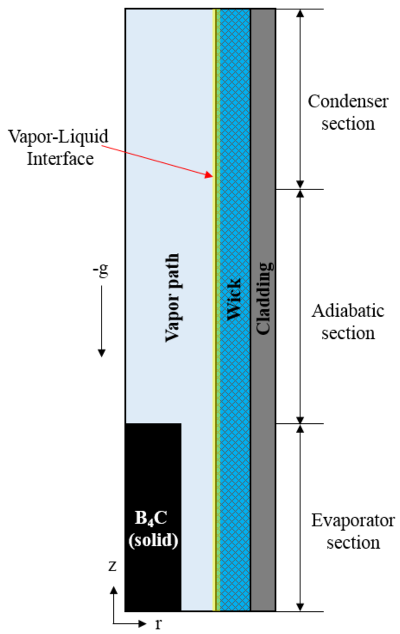


Fig. 2 Physical domain of the single hybrid heat pipe simulation

3. Results and Discussions

3.1 Single hybrid heat pipe simulation

Numerical analysis of hybrid heat pipe was performed by solving continuity, momentum and energy equations of each domain to evaluate the thermal performance. In the simulation, reactor environment conditions were considered as boundary condition. At the right of reactor shutdown and coolant flow stop, bulk temperature of coolant near the active core is about 320 °C. With given condition, total 18.20 kW of heat is transported through the hybrid heat pipe. To evaluate the overall thermal performance of hybrid heat pipe, total thermal resistance was calculated. From predicted results, total thermal resistance of the current hybrid heat pipe is about 0.0148 °C/W. Interface temperature between vapor and liquid is 217.34 °C at maximum and 201.25 °C at minimum so that boiling and condensation inside heat pipe have no problem in operation with considering the saturation temperature of working fluid. Especially, maximum vapor velocity is about 6 m/s at the end of evaporator side, which is at the location in sudden increase of the cross sectional area of vapor path due to installed cylindrical B_4C pellet in evaporator region. It implies that vapor flow can have behavior of the local transition flow. Maximum vapor pressure drop in vapor path is about 350 Pa between evaporator end sides, which also means that the additional model for predicting flow in vapor path may be necessary for more accurate solution. However, in this study, it can be negligible in evaluating overall thermal performance of the hybrid heat pipe. Thermal performances for the hybrid heat pipe are summarized in Table. I.

Table. I Summary of single hybrid heat pipe simulation

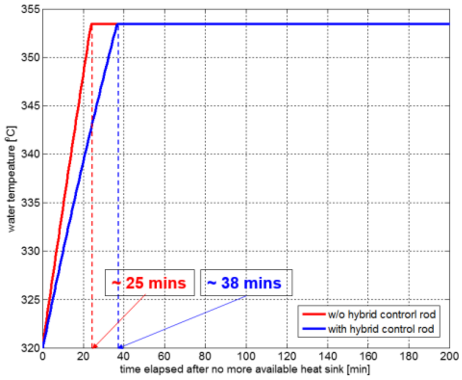
Parameters		*Value*
T_{avg}	Evaporator region	320 °C
	Adiabatic region	256 °C
	Condenser region	50 °C
T_{int}	Maximum	217.34 °C
	Minimum	201.25 °C
Total amount of heat removed		18.20 kW
Total thermal resistance		0.015 °C/W

3.2 1D T/H reactor transient analysis

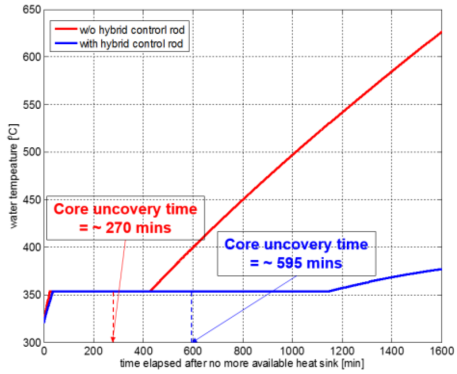
Figure 3 (a) and (b) show the results of reactor transient analysis with respect to the time elapsed after no more heat sink is available for the normal reactor case and reactor with hybrid heat pipe case. For normal reactor, time to reach the saturation temperature, about 344.76 °C at 155 bar is only about 25 minutes from considered point. Hybrid heat pipe can delay time required for boiling of coolant about 13 minutes. Unfortunately, both of two cases showed the possibility of the core uncovery. However, core uncovery was delayed about 325 minutes with hybrid heat pipe compared to the normal reactor, which means that response time to unexpected situation can be secured.

Figure 3 (c) shows the reactor coolant temperature since no more heat sink is available after reactor shutdown for the normal reactor case, and reactor with several improved hybrid heat pipe cases. With enhanced hybrid heat pipe having 1.5 times and 2.5 times improved capacity, they showed no core uncovery within 1 day from considered point, which is enough time to cope with emergency situation of reactor. Especially, hybrid heat pipe having 2.5 times improved capacity can keep cooling the reactor and coolant temperature was maintained below boiling temperature. For that case, coolant temperature started to decrease after 150 minutes after time elapsed after considered point. Figure 3 (d) shows the comparison between amount of decay heat from considered point and that of removed by hybrid heat pipe. Maximum reactor temperature is 335.83 °C and maximum amount of heat removal is 35.64 MW.

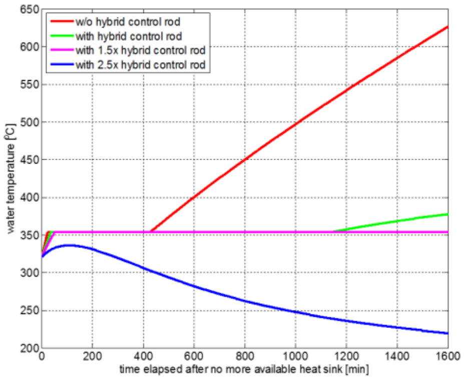
Fig. 3 Result of reactor transient analysis compared with normal reactor and reactor with hybrid heat pipe



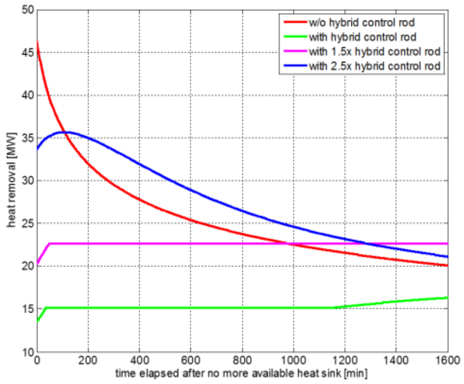
(a) Reactor temperature change and time required to boil the coolant



(b) Reactor temperature change and time required to core uncovery



(c) Reactor temperature change with various capacity hybrid heat pipe



(d) Heat generated for normal reactor and amount of heat removed by hybrid heat pipe case of various capacities

4. Conclusions

As a passive decay heat removal device, hybrid heat pipe was suggested with a concept of combination of heat pipe and control rod. Hybrid heat pipe has distinct feature that it can be a unique solution to cool the reactor when depressurization process is impossible so that refueling water cannot be injected into RPV by conventional ECCS. It contains neutron absorber material inside heat pipe, so it can stop the reactor and at the same time, remove decay heat in core. For evaluating the concept of hybrid heat pipe, its thermal performance was analyzed using CFD and one-dimensional transient analysis. From single hybrid heat pipe simulation, the hybrid heat pipe can transport heat from the core inside to outside about 18.20 kW, and total thermal resistance of hybrid heat pipe is 0.015 °C/W. Due to unique features of long heat pipe and high-temperature high-pressure condition, hybrid heat pipe should be analyzed with additional effect from local transitional flow of vapor. For evaluating cooling performance of the hybrid heat pipe as PINCs, reactor transient analysis was done to calculate the temperature change after no more heat sink for decay heat removal is available. From 1-d reactor transient analysis, time required to boil the water in RPV is delayed about 13 minutes, and core uncovery time is delayed about 5.4 hours with hybrid heat pipe, assuring the response time in accident situation. If hybrid heat pipe have 2.5 times improved cooling capacity, it can keep cooling the reactor preventing evaporation of the coolant and have no core uncovery within 1 day from considered point.

Therefore, hybrid heat pipe can work well as a PINCs, combined with control rod and heat pipe having same drive mechanism with traditional control rod in station blackout accident and its extensions.

ACKNOWLEDGEMENTS

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