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Design of Passive Containment Cooling System of PWR using Multi-pod Heat Pipe

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1. Introduction

As we have seen in the Fukushima nuclear crisis, major accident is not just a hypothetical accident. As in a BWR nuclear power plant, a containment is the last bastion against radiation leakage for a PWR nuclear power plant. The wholesomeness the containment is directly connected with the safety of a nuclear power plant. Therefore, a passive cooling system for the containment is required to prevent a major accident of the nuclear power plant. This study perfected the conceptual design about the Passive Containment Cooling System (including a suppression pool) using Multi-pod Heat Pipe(MPHP) that meets the requirements of air-tightness and economic feasibility.

2. Design of Passive Containment Cooling System

2.1. Design requirements of MPHP

2.1.1. Decay Heat

For APR1400, the time to reach FLC(Factored Load Category) is calculated with the precision code to be 24 hours. This means that the decay heat produced within 24 hours from the accident is removed through coolant inside the reactor, the reactor core structure, internal air of the containment, and external heat transfer from structures and containment building. Therefore, the wholesomeness of containment is not threatened any more if the delay heat produced after 24 hours can be cooled down. The decay heat is reduced after a day to approximately 0.5% of the thermal output under normal operation. Therefore, the heat of 16.97MWt needs to be removed.

2.1.2. Determine the operation range and the fluid

The fluid to be used in MPHP must provide the characteristics required for the passive cooling system for the containment. In other words, it must fulfill the chemical and thermal requirements. In this study, pure water was selected as the fluid for MPHP. In consideration of the operation range (90℃ ~ 180℃), the selected charging pressure was approx. 0.7atm.

2.2. Design of Multi-pod Heat Pipe

When simply applying heat pipes for cooling of the containment building, tens of thousands of heat pipes and pipe holes are required in consideration of the tremendous amount of heat to be cooled down. In order to minimize the number of pipe holes, the heat insulating parts (the penetrating parts of the containment building) were integrated into a single cylinder. This enables structural reinforcement of the heat pipe insulating part wall which is not related with heat transfer, robust installation of pipes in the reactor building, and easy maintenance and repairing. Evaporator and condenser must transfer heat (boiling and condensation) smoothly, and therefore, they were designed to have many heat pipes.

2.2.1. MPHP Assembly

MPHP was designed in hexagonal array with the superior compact. Where P/D=2, D=2.5cm, P=5cm, a side of the assembly is 165cm in length. It is approx. 170cm if the shroud thickness of the assembly is included. Conservatively, an assembly diameter is approx. 2m. Considering the room of 50% and to raise reliability of the system, they were installed evenly in many places (3 places) to minimize pipe holes. When 3 heat pipe assemblies are installed, 3,000 pins are allocated to each assembly, and to allocate 3,000 heat pipes, grates are required in 32 lines. The total number of the pins is 3,118, and supporting structures are installed to support the grates in some pin positions.

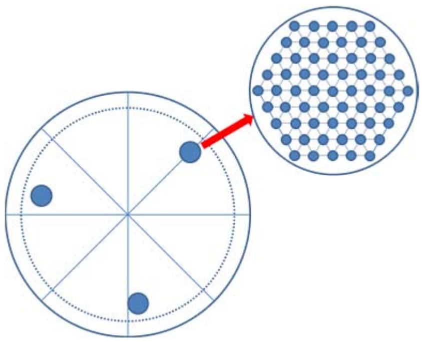

Fig 1. Sketch of Heat Pipe Assembly

2.3. Security of cooling water

The required elements include the sufficient water resource for cooling operation, the pipes required to transfer water to the top of the containment, and the nitrogen tank that provides the pressure required to transfer water. The coolant transferred to the top of the containment must have sufficient water level and amount to have MPHP submerged (sufficient height over the top of MPHP). For this purpose, it is required to install a MPHP tank outside the containment. To utilize the space and to minimize cost, the containment cylinder is extended and walled, and the external space of the dome is used for the tank and MPHP.

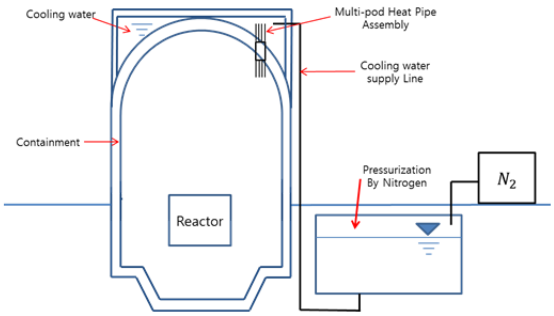

Fig 2. Design of Passive Cooling system

2.3.1. Volume of the water tank

As mentioned above, if the cooling water tank for MPHP is installed outside of the containment dome, it is required to calculate if the volume (coolant capacity) of the tank is sufficient. First, for simplicity of calculation, assume the extension of the outer wall of the containment as the outer wall of the water tank, and that the tank has the same height as the dome.

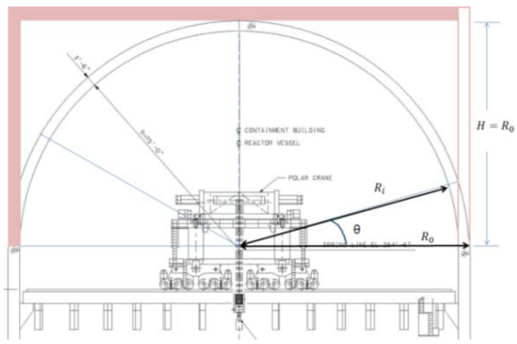

Fig 3. calculation of the space of the MPHP and related facilities

Volume of the water tank

= Volume of the cycle - Volume of the dome

– Volume of the cylinder shape + Volume of the wall (1)

The result of the calculation is that 30TON/hr of coolant is required in order that 18MWt of heat should be removed. Therefore, 2,610TON is required for 72 hours after the accident. The volume of the tank calculated with the specifications of APR1400 containment is 11,403 m^3 , which is sufficient to accommodate the required amount of coolant.

2.4. Checking the Critical Heat Flux

In designing of heat pipe, it is required to check the Critical Heat Flux(CHF) of the boiling part. Based on 1400MWe, the thermal output of the reactor is 4000MWt, and the decay heat in one day after the operation is stopped is approx. 18MW, which is 0.5%. With the pipe with the inside diameter of 2cm and the length of 3m, CHF is approx. $5.3kW/m^2$ at 130℃.

$$q'' = \frac{1kW}{\pi DH} = 5.3kW/m^2 \quad (2)$$

When calculating CHF from the Zuber's CHF correlation on pool boiling, it is

$$\mathrm{CHF} = k h_{fg} \rho_g^{1/2} [\sigma g(\rho_f - \rho_g)]^{1/4} = 7.9\mathrm{kW}/m^2 \quad (3)$$

The probability of CHF will be barely occurred in this case. The above mentioned correlation is applied to the upward plate heater. CHF of the vertical wall heater is higher than that of the plate heater.

3. Conclusions

In this study, the conceptual design of the passive containment vessel cooling system using MPHP was established. Further studies are required for optimum design, system configuration and verification through simulation and verification test based on this conceptual design of MPHP.

NOMENCLATURE

P = Length of the Pitch
R = Radius
t = thickness of dome
D = diameter
H = height
k = $\pi/24$
h_{fg} = *latent heat of vaporization*
σ = *surface tension*
ρ = density
g = gravity acceleration

Subscript
i = inner
o = outer
f = saturated liquid water
g= saturated vapor water

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