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Heat Transfer Modes and their Coefficients for a Passive Containment Cooling System of PWR using a Multi-Pod Heat Pipe

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1. Introduction

If a reactor core is damaged due to a disaster such as happened at TEPCO's Fukushima nuclear power plant, the inevitable rise of super-heated steam that could potentially convert to hydrogen resulting from unimpeded temperature and pressure rises will threaten the integrity of the containment structure.

To prevent this, safety and regulatory standards typically specify that the gas vent and external cooling systems be designed to maintain containment up to the level C limit for 24 hours and integrity for 48 hours after any damage to the core. Furthermore, it is recommended that the installation of the exhaust penetration unit have a minimum diameter of 3ft. However, installation of such cooling measures or penetration units is burdensome in terms of operational and maintenance costs not to mention the need to ensure a fleet of fire trucks to be on standby as well as the need to ensure a plentiful supply of water for cooling and a filtration system to clean the water.

Therefore, the development of a reliable passive cooling system will be economically advantageous because the extra cost burdens of the external system can be omitted. The Passive Containment Cooling System (PCCS) using a multi-pod heat pipe proposed in this study satisfies these conditions [1].

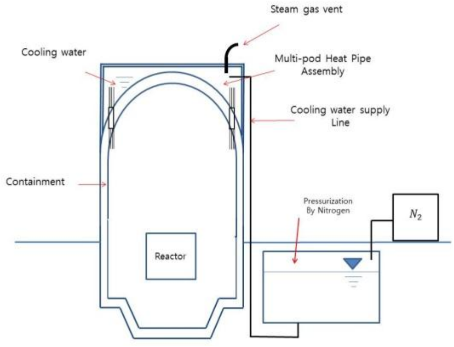

Fig.1 Design concept of an MPHP

The Multi-Pod Heat Pipe (MPHP) is a thermo-siphon heat exchanger that takes advantage of gravity for heat transfer occurring due to temperature differences. For the MPHP to achieve its performance target it is critical that it be designed for efficient heat exchange. To realize this, it is essential to understand the heat transfer modes of the MPHP and determine the corresponding heat transfer coefficient. Therefore, in this study, the heat transfer modes and the corresponding heat transfer coefficient of the MPHP were determined.

2. Heat transfer modes

The heat pipe is broadly divided into a boiling region, adiabatic region and condensation region. The heat transfer modes (boiling and condensation) occur according to the temperature difference in each region. This phenomenon is depicted in Fig. 2.

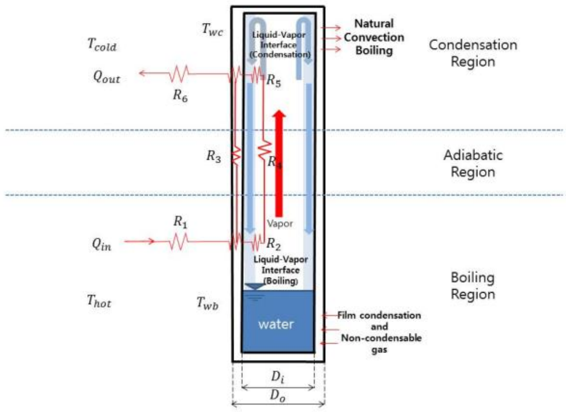

Fig.2 Heat Transfer modes in an MPHP

2.1. Boiling and Condensation Regions

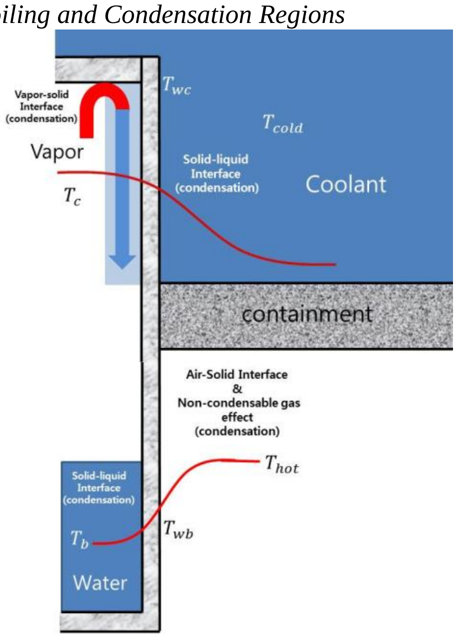

Fig.3 Heat transfer modes in the boiling and condensation regions

Above the boiling region, steam rises and then begins to condense between the heat pipe walls. In the outer wall, air, which is a non-condensable gas (NC), accumulates near the wall surface and hinders condensation. Particularly during a serious accident, as the inside of the containment is cooled by natural circulation, the non-condensable gas greatly affects the efficiency of heat transfer.

Inside the boiling region, the latent heat of the working fluid is transferred through the boiling process. At this phase, heat transfer occurs by the working fluid at the bottom of the heat pipe and the liquid film on the wall of the boiling region.

Outside the condensation region, the outer wall of the heat pipe is cooled by the cooling material that is cooler than the outer wall of the heat pipe, and boiling heat transfer occurs by natural convection from the outer wall to the cooling material.

Inside the condensation region, film condensation occurs as the steam rising up from the boiling region condenses on the inner wall of the condensation region.

2.2. Adiabatic Region

It is expected that the adiabatic region would not have such a big influence on the overall heat transfer because the temperature variation there is not large [4]. In this study, 5℃ was assumed for the temperature difference in the adiabatic region and applied to the thermal calculation. This needs to be proven through further experiments.

3. Heat transfer coefficients

2.1. Boiling Region

Outside the boiling region, the non-condensable gas influences condensation as mentioned above, the heat transfer coefficient is expressed using the Uchida correlation:

$$h_{NC} = 380\left(\frac{W_{NC}}{1 - W_{NC}}\right)^{-0.7} \; [W/m^2 \cdot K]$$

The heat transfer coefficient inside the boiling region is expressed by the following equation for the boiling correlation of the pool which is limited by the height of the vertical cylinder:

$$h_b = 0.32x\left(\frac{P_i}{P_o}\right)^{0.3} \; [W/m^2 \cdot K]$$

$$x = \frac{\rho_l^{0.65} \, k_l^{0.3} \, C_{pl}^{0.7} \, g^{0.2} \, q_e^{0.4}}{\rho_v^{0.25} \, h_{fg}^{0.4} \, \mu_l^{0.1}}$$

2.2. Condensation Region

For the boiling heat transfer coefficient outside the condensation region, the Forster and Zuber correlation was applied.

$$h_{Cold} = \frac{0.00122 \Delta T^{0.24} \Delta P^{0.75} \, C_p^{0.45} \, \rho_l^{0.49} \, k_l^{0.79}}{\sigma^{0.5} \, h_{fg}^{0.24} \mu_l^{0.29} \, \rho_v^{0.24}} [W/m^2 \cdot K]$$

Finally, inside the condensation region the Nusselt correlation related to film condensation was applied.

$$h_c = \; 0.943\left(\frac{k_l^3 \rho_l^2 g l_{fg}}{\mu_l \Delta T_c L_c}\right)^{1/4} [W/m^2 \cdot K]$$

2.3. Overall heat quantity

Based on the heat transfer coefficients, the total heat quantity can be summarized as follows [5].

$$\dot{Q} = \frac{T_{hot} - T_{cold} - 5℃}{\left(\frac{1}{A_o h_{NC}} + \frac{\ln(D_o/D_i)}{2\pi k_{wb} L} + \frac{1}{A_i h_b} + \frac{1}{A_i h_c} + \frac{\ln(D_o/D_i)}{2\pi k_{wc} L} + \frac{1}{A_o h_{Cold}}\right)} [W]$$

4. Conclusion

When the heat transfer modes and heat transfer coefficients are applied, the longer the pipe and the greater the temperature difference, the greater the exchangeable heat quantity becomes as shown in Fig.5. Details will be proven through a subsequent empirical experiment planned for a later date.

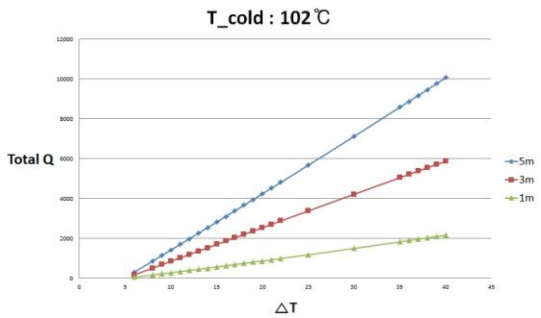

Fig.6 Change of overall heat quantity

NOMENCLATURE

W = Mass fraction
Q = Quantity of heat , P = pressure
ρ = Density , h = heat transfer coefficient
k = Thermal conductivity coefficient
C_p = Specific heat
g = Gravity , q_e = Radical heat flux
l = Latent heat , μ = viscosity coefficient

Subscript
NC = Non-condensable gas
wc = Wall of the condensation region
wb = Wall of the boiling region
i =inner , o = outer , v = Vapor
l =Liquid , fg = Saturated vapor and saturated liquid

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