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Conceptual Design of Passive Containment Cooling System for Concrete Containment

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Abstract

A study on passive cooling systems for concrete containment of advanced pressurized water reactors has been performed. The proposed passive containment cooling system (PCCS) consists of (1) condenser units located inside containment, (2) a steam condensing pool outside containment at higher elevation, and (3) downcommer/riser piping systems which provide coolant flow paths. During an accident causing high containment pressure and temperature, the steam/air mixture in containment is condensed on the outer surface of condenser tubes transferring the heat to coolant flowing inside tubes. The coolant transfers the heat to the steam condensing pool via natural circulation due to density difference. This PCCS has the following characteristics: (1) applicable to concrete containment system, (2) no limitation in plant capacity expansion, (3) efficient steam condensing mechanism (dropwise or film condensation at the surface of condenser tube), and (4) utilization of a fully passive mechanism. A preliminary conceptual design work has been done based on steady-state assumptions to determine important design parameters including the elevation of components and required heat transfer area of the condenser tube. Assuming a decay power level of 2%, the required heat transfer area for 1,000 MWe plant is assessed to be about 2,000 m^2 (equivalent to 1,600 of 10-m-long, 4-cm-OD tubes) with the relative elevation difference of 38 m between the condenser and steam condensing pool and the riser diameter of 0.62 m.

1. Introduction

In a pressurized water reactor(PWR), containment is an important system for ultimate safety of the plant against the leakage of radioactive material to environment. However, without efficient removal of core decay heat continuously generated even after reactor shutdown, containment pressure or temperature may exceed the design values causing the containment failure.

To prevent the unfortunate event from happening, containment cooling system, which can remove the energy released to containment environment (primary coolant and core decay heat) is required. In conventional nuclear power plants, containment spray system and/or fan cooler systems play the role of containment cooling. However these systems are all active and demand external electric power source.

PCCS concepts proposed for advanced PWRs are mainly for steel containment. However most existing PWR plants such as Korea Standard Nuclear Power Plant (KSNPP) have concrete containment. Concrete containment system has advantages over the steel one in several aspects: operating and construction experience, low cost, small design changes required etc. Therefore the concrete containment system has been adopted in the large passive PWR concept under development by the Center for Advanced Reactor Research[1]. A passive cooling system for that concrete containment[1] has been designed conceptually, and the design parameters are presented in this paper.

2. Overview of PCCS for Concrete Containment

In concrete containment, the containment itself cannot be used as the heat conduction media such as steel containment of AP600. Thus, to reduce containment pressure and temperature in accident condition, energy or energy-containing material in containment should be either extracted through the containment wall or transferred via another heat transfer media.

Figure 1 shows the cooling concept adequate for concrete containment. The primary coolant and emergency safety injection coolant are released to containment environment having core decay heat. The discharged coolants are condensed at the outer surface of condenser tube as transferring the decay heat to cooling system coolant. The enhancement of condensation heat transfer can be accomplished by condenser tube surface. Doing this, the dropwise condensation can be maintained.

The energies make cooling system coolant less dense or boil, which drive circulation of coolant in cooling system. The decay energy is transported by circulating coolant to condensing pool where the boiling water condensed by direct contact condensation with the pool water.

3. Natural Circulation Loop

In two phase natural circulation, the governing equations can be written as following mixture equations.

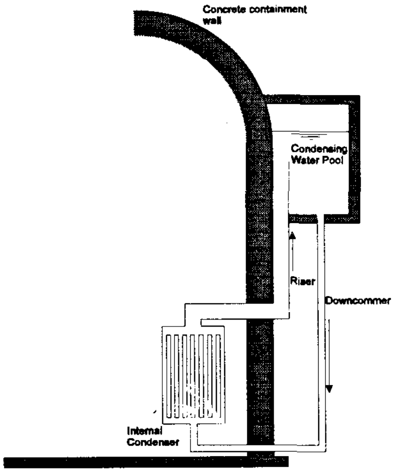

Figure 1. General Layout of Designed PCCS for Concrete Containment

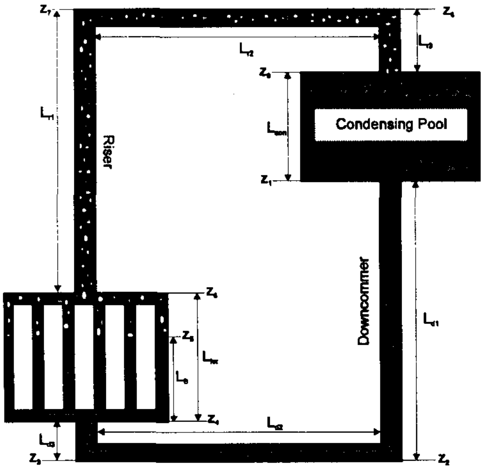

Figure 2. Modeling of Two Phase Natural Circulation

$$W = W_f + W_g = \text{constant} \tag{1}$$

where $W_f = \rho_f v_f A_f$ and $W_g = \rho_g v_g A_g$

$$-\frac{dp}{dz} = \frac{4\tau_w}{D} + G\frac{d}{dz}[xv_g + (1-x)v_f] + g[\alpha\rho_g + (1-\alpha)\rho_f]\cos\theta \tag{2}$$

Governing equations can be integrated section by section of natural circulation system.

The simplified modeling of PCCS is shown in Figure 2.

In downcommer section, the flow is in single phase state, which means the quality x and void fraction α of Equation (2) is zero. In this case, the momentum equation is written as

$$\Delta p_d = p_{z_4} - p_{z_1} = -f_d \frac{2\dot{m}^2 L_d}{\rho_d D_d A_d} + \rho_d g(L_{d1} - L_{d3}) \tag{3}$$

In condenser, the decay heat is transferred to coolant, resulting in boiling of circulating water. Before the coolant begin boiling, the flow is in single phase. As the coolant absorb decay heat, the density may change although very small compared to that of vapor.

Generally in single phase natural circulation, the density difference is given as:

$$\rho = \rho_d\{1 - \beta(T - T_d)\} \qquad (T_d \le T \le T_f) \tag{4}$$

The temperature is assumed to change linearly dependent to the height difference between coolant inlet and saturation reaching point.

$$T(z) = \frac{T_f - T_d}{L_B} z + T_d \qquad (0 \le z \le L_B) \tag{5}$$

The momentum equation in single phase section of condenser is written as:

$$\Delta p_{con1} = p_{z_5} - p_{z_4} = -\frac{2 f_{con1} \dot{m}^2}{D_{con} A_{con}^2 N^2} \frac{L_B}{\rho_d - \rho_f} \ln\left(\frac{\rho_d}{\rho_f}\right) - \frac{\dot{m}^2}{A_{con}^2 N^2}\left\{\frac{1}{\rho_f} - \frac{1}{\rho_d}\right\} - \frac{\rho_d + \rho_f}{2} g L_B \tag{6}$$

If natural circulation only occurs in single phase, L_B, the boiling-begin length is substituted by L_{con}.

In calculation of single phase pressure drop, The friction factor f should be well described. In this study, Chen's correlation[2] is adapted.

$$f = 4\left\{3.48 - 1.7372\ln\left[\frac{2\varepsilon}{D} - \frac{16.2426}{\mathrm{Re}}\ln\left(\frac{(2\varepsilon/D)^{1.1098}}{6.0983} + \left(\frac{7.149}{\mathrm{Re}}\right)^{0.8981}\right)\right]\right\}^{-2} \tag{7}$$

Two phase flow pressure drop relation in boiling region of condenser tube can be expressed as following forms[3]:

$$\Delta p_{con2} = -\frac{2G^2 f_{fo}}{D\rho_f}\int_0^{L-L_B} \phi_{fo}^2 dz - G^2\left\{\frac{x_{exit}^2}{\rho_g \alpha_{exit}} + \frac{1}{\rho_f}\left[\frac{(1-x_{exit})^2}{(1-\alpha_{exit})} - 1\right]\right\} + g\int_0^{L-L_B}\{\alpha\rho_g + (1-\alpha)\rho_f\}dz \tag{8}$$

In this case, at $z = 0$, $x = 0$ and at $z = L - L_B$, $x = x_{exit}$.

In heated condenser tube section, the density is assumed to increase linearly with the height.

$$x = \frac{x_{exit}}{L - L_B} z \qquad (0 \le x \le x_{exit}, 0 \le z \le L - L_B) \tag{9}$$

There are two significant factors in calculating the pressure drop of two phase flow. One is calculation of two phase frictional multiplier and the other is void fraction along heated tube section.

Two phase frictional multiplier can be obtained by Friedel's correlation[4]:

$$\phi_{fo}^2 = (1-x)^2 + x^2\left(\frac{\rho_f f_g}{\rho_g f_f}\right) + \frac{3.21x^{0.78}(1-x)^{0.224}\left(\rho_f/\rho_g\right)^{0.91}\left(\mu_g/\mu_f\right)^{0.91}\left(1-\mu_g/\mu_f\right)^{0.7}}{\left(G^2/\rho_{TP}^2 gD\right)^{0.0454}\left(GD/\rho_{TP}\sigma\right)^{0.035}} \tag{10}$$

where f_f, f_g : friction factors for single phase liquid and vapor of same mass flow rate

$\rho_{TP} = \left[\frac{x}{\rho_g} + \frac{(1-x)}{\rho_f}\right]^{-1}$: two phase density

For riser region, the momentum equation is similar to Equation (8). But in this region quality and void fraction may not change through flow area.

$$\Delta p_r = -\frac{2G_r^2 f_{fo} L_r}{D_r \rho_f}\phi_{fo}^2 + g\{\alpha_{exit}\rho_g + (1-\alpha_{exit})\rho_f\}(L_{r3} - L_{r1}) \tag{11}$$

In condensing pool momentum equation give following pressure drop.

$$\Delta p_{pool} = p_{z_1} - p_{z_9} = -\frac{\dot{m}^2}{A_{con}^2}\left(\frac{1}{\rho_d} - \frac{1}{\rho_{exit}}\right) - f_{pool}\frac{2\dot{m}^2 L_{pool}}{\rho_d D_{pool} A_{pool}^2} + \rho_{pool} g L_{pool} \tag{12}$$

The void fraction can be obtained from following EPRI (Chexal-Lellouche) correlation[5].

$$\langle\alpha\rangle = \langle j_g\rangle \Big/ C_o\langle j_f + j_g\rangle + v_{gj} \tag{13}$$

The EPRI correlation is iterative one based on drift flux model formulation, and acceptable in wide range regardless flow regime.

In calculating the pressure drop for given system, it is necessary to consider pressure loss due to form loss factor. Form loss factor is given as following equation.

$$\Delta p_{form} = K\frac{\rho v^2}{2} = K\frac{\dot{m}^2}{2\rho A^2} \tag{14}$$

where K is given in each case of sudden expansion, sudden contraction, elbow for single and two phase.

$$K_{se} = \left(1 - \tfrac{A_0}{A_1}\right)^2,\ K_{sc} = \tfrac{1}{2}\left(1 - \tfrac{A_0}{A_1}\right)^{\frac{3}{4}},\ K_{se} = \left(1 - \tfrac{A_0}{A_1}\right)^2\left[1 + \tfrac{v_{fg}}{v_f}x\right],\ K_{sc} = \left[\left(\tfrac{A_0}{A_c} - 1\right)^2 + \left(1 - \tfrac{A_0}{A_1}\right)^2\right]\left[1 + \tfrac{v_{fg}}{v_f}x\right] \tag{15}$$

where A_0 and A_1 is the cross sectional areas of narrow and wide regions respectively. In elbow K_{elbow} is selected to 0.6.

Summing the equation (3, 6, 8, 11, 12) with appropriate form loss factor gives natural circulation relation between mass flow and pressure drop factors.

4. Design and Analysis of Cooling System

One of the most important factor in design of passive containment cooling system is heat transfer area of heat exchanger, i.e., condenser. To evaluate the heat transfer area, following energy balance relations are introduced.

In this study, the target value is required heat transfer area for decay power level 2% of 1,000 MWe (2,815 MWt) nuclear power plant. First heat transfer relation from containment environment to condenser can be written as:

For single phase,

$$Q_d = UA\Delta T_{ln} = \frac{UA(T_{out} - T_{in})}{\ln\left({T_c - T_{in}} \middle/ {T_c - T_{out}} \right)} \tag{16}$$

For two phase,

$$Q_d = U_1 A_1 \frac{T_c - T_{in}}{\ln\left({T_c - T_{in}} \middle/ {T_c - T_{out}} \right)} + U_2 A_2 (T_c - T_{sat}) \tag{17}$$

where, the overall heat transfer coefficient U is given by following equation.

$$U = \left[\frac{1}{h_c} \frac{D_o \ln\left({D}/{D_i} \right)}{2k} + \frac{1}{h_b} \right]^{-1} \tag{18}$$

The h_c means condensation heat transfer coefficient. Condensation heat transfer coefficient has large variation range according to the T/H conditions and surface condition. So sensitivity study is accomplished with basis on Dehbi's experimental data[6], h_c = 600kW/m^{2}K.

The h_b is given for single and two phase as followings.

$$h_b = \begin{cases} 0.023 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4}\, {k}/{D_i} & \text{for single phase} \\ 1.9712 e^{(\%_{\omega})} (T_w - T_{sat}) = 7.91 \times 10^4\, \mathrm{W/m^2K} & \text{for two phase} \end{cases} \tag{19}$$

Inside of tube, the relation between absorbed heat and temperature or enthalpy change is given as:

$$Q_d = \dot{m} C_p (T_{out} - T_{in}) \text{ for single phase, } Q_d = \dot{m} C_p (T_{sat} - T_{in}) + x_{exit} \dot{m} (h_g - h_f) \text{ for two phase.} \tag{20}$$

With given thermal power, geometry and obtained mass flowrate, the required heat transfer area are calculated in energy balance equations.

To figure out the most affecting parameters to required heat transfer area, sensitivity studies are performed for head difference, coolant inlet temperature, riser diameters, condensation heat transfer coefficient.

The data for calculation of required heat transfer area are presented in Table 1.

Table 1. Data for Design of PCCS

Symbol	Description	Note	Symbol	Description	Note
ρ_c [kg/m^3]	density in cold side	995.75	ρ_f [kg/m^3]	density of saturated water	958.39
ρ_{exit} [kg/m^3]	density at the exit of condenser	To be calculated	β [K^{-1}]	thermal expansion coefficient of water	0.0005372
μ_g [kg/m·s]	viscosity of saturated steam	0.000012	μ_f [kg/m·s]	viscosity of saturated water	0.00028
L_{d1} [m]	down flow length of DC	30, 40, 50	L_{d2} [m]	horizontal length of DC	5
L_{d3} [m]	up flow length of DC	2	L_{con} [m]	length of condenser tube	10
L_{r1} [m]	up flow length of riser	30, 40, 50	L_{r2} [m]	horizontal length of riser	2
L_{r3} [m]	down flow length of riser	5	L_{pool} [m]	elevation of pool	10
L_B [m]	boiling reaching length	To be calculated	T_d [°C]	temperature of cold side	30, 60, 90
T_{exit} [°C]	temperature at the exit of condenser	To be calculated	x_{exit}	quality at the exit of condenser	To be calculated
N	number of condenser tubes	To be calculated	D_d [m]	diameter of DC	0.1
D_{con} [m]	dia. of condenser tube	0.04	D_r [m]	dia. of riser	0.31, 0.62, 0.93
D_{pool} [m]	dia. of condensing pool	8	h_c [kW/m^{2}K]	condensation heat transfer coefficient	600, 1,200, 2,400

5. Results and Discussion

The analysis results are presented in Figure 3 to Figure 6.

Figure 3 shows the established mass flow with changing riser diameter size. Mass flowrate show large difference between 0.31m-dia. and others. This is because the two phase frictional pressure drop is much large in 0.31m-dia.than other ones. Moreover if the decay power level exceed 1.5%, the coolant reaches superheated state in 0.31m-dia. tube. The difference of mass flow between 0.62m-dia.and 0.93m-dia.is rather small. This means that the riser diameter become larger enough than any limit, friction effect of riser section due to two phase flow have no importance than those of others. Similar behavior can be seen in Figure 4, "Required Heat Transfer Area for Riser Dia. Change". The heat transfer area for 0.62m-dia. and 0.93m-dia. tubes are nearly same.

Condensation heat transfer coefficient has wide range according to many conditions. They have ranges of about 10^2 to 10^5W/m^{2}K. In this study, Dehbi's experimental data are based and sensitivity study are performed. The results are presented in Figure 5. Though the h_c increases twice, the required heat transfer area decrease only ¾ of original case. But if h_c decreases ½, the required heat transfer area are increases 1.8times. Therefore, maintaining h_c as possible as large is very important.

Other parameters are of little importance in heat transfer coefficient. As a result of sensitivity study, Following design parameters are determined.

Table 2 Designed Parameters of PCCS

Parameter	Value	Parameter	Value
D_r [m]	0.62	D_d [m]	0.1
L_{con} [m]	10	L_{pool} [m]	10
D_{con} [m]	0.04	D_{pool} [m]	8
L_d [m]	47	L_r [m]	47
A [m2]	2,000	Number of tubes	1,600

In Figure 6, Required heat transfer area and associated tube numbers are shown as a function of decay power level.

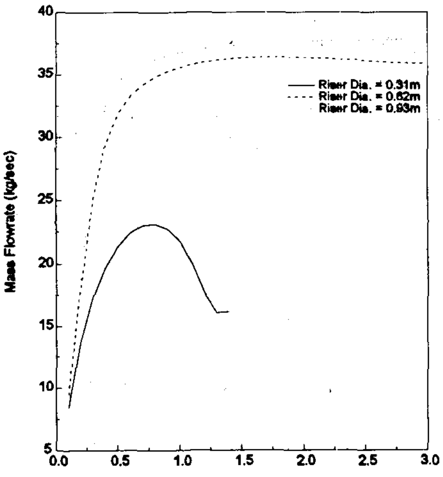

Figure 3. Established Mass Flowrate for D_r Change

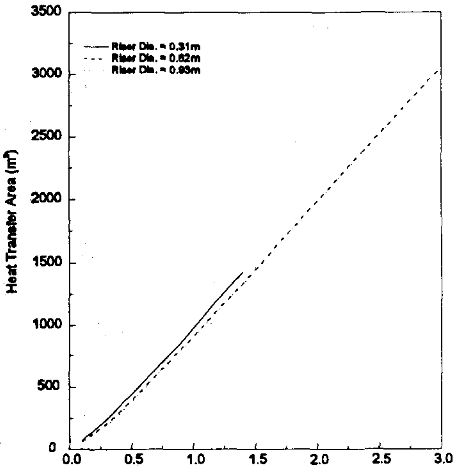

Figure 4. Required Heat Transfer Area for D_r Change

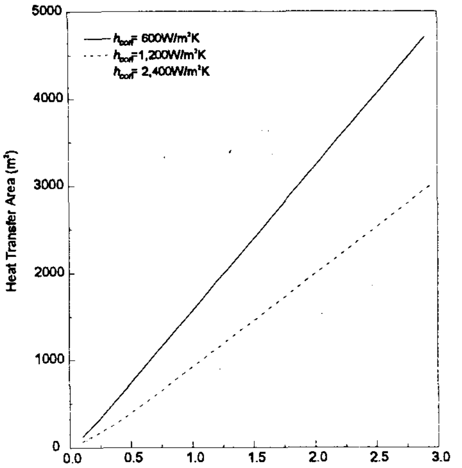

Figure 5. Required Heat Transfer Area for h_{con} Change

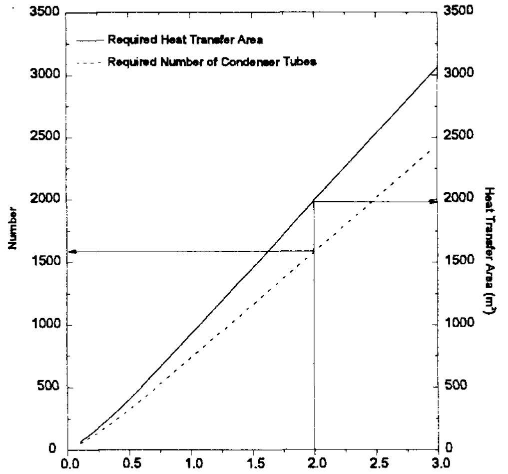

Figure 6. Designed Parameters of PCCS

6. Conclusions and Recommendations

In this study, the conceptual design of a PCCS for the PWR concrete containment has been performed.

The designed PCCS consists of condenser units located inside containment, steam condensing pool outside containment at higher elevation, and downcommer/riser piping systems which provide coolant flow path in PCCS. During an accident causing high containment pressure and temperature, the decay heat transferred to steam condensing pool via two phase natural circulation of coolant in PCCS.

Based on simple steady-state calculations, the required heat transfer area of condensers is found to be about 2,000m² for 2% decay heat removal of 1,000 MWe plant, with relative height of condenser and condensing pool 38m.

Parametric studies for several design parameters have also been performed.

As a future work, performance analysis should be accomplished for the conceptual design parameters with a system analysis code such as RELAP5. Through performance analysis, verification and optimization of design parameters can be done.

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