Study on the Design of Passive Containment Heat Removal System

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Abstract. The containment is the last barrier to prevent the release of radioactive material into the environment after an accident. If the pressure of the containment vessel exceeds the ultimate carrying capacity of the containment, a large amount of radioactive material leaks into the external environment after the accident. The author designs a set of passive containment cooling system based on sea shipping space constraints. The head period of cold leg double side shear fracture accident of long-term containment thermal response is analyzed in detail. The analysis results show that the loss of coolant accident occurs within 72h, the passive containment cooling system can ensure the safety of pressure, which meets the design requirements.

1. Introduction
At present, the pressurized water reactors in service in China are equipped with containment spray systems to ensure that the pressure and temperature in the containment remain within a safe range after the occurrence of accidents beyond the designed benchmark [1].

Based on the space limitation of ships at sea and the availability of safe power supply, the safe dynamic spray system is not considered. In this paper, a containment passive heat extraction system is designed. When water loss occurs in the containment and the temperature and pressure inside the containment rise, water inside the secondary shielding water jacket outside the containment is used to absorb the heat inside the containment and keep the containment temperature and pressure within the limit value to ensure the integrity of the third barrier. In this paper, a detailed analysis is made on the thermal engineering of the containment vessel in the medium and long term in which the double-end shear fracture of the main section occurs, and the rationality of the design of the passive heat extraction system of the containment vessel in this paper is demonstrated.

2. System Composition and Operation Mode
The schematic diagram of the containment passive heat extraction system is shown in figure 1. The system consists of containment wall, shielding water jacket and corresponding exhaust pipe.

After the occurrence of water loss accident, the pressure rise in the containment vessel can be quickly suppressed by the suppression pool in a short term, and the heat in the containment vessel can be derived by the shielding water jacket in the containment vessel in a medium and long term. The shielding jacket works by heating the core with decay heat to water vapor, which condenses on the inner wall of the containment vessel. The heat released by the vapor is transferred to the water
inside the containment vessel, which absorbs heat and increases the temperature. Through this process, the heat in the containment vessel can be derived so that the temperature and pressure in the steel containment vessel do not exceed the design value, ensuring the integrity of the third shielding layer.

![Figure 1. Structure Diagram of the Passive Containment Cooling System.](image)

3. Analysis Methods and Models
The physical phenomena related to the passive heat transfer system of the containment can be represented by the empirical relationship of heat transfer, and the whole physical process is described according to the mechanism of heat transfer and the corresponding empirical relationship of heat transfer. The whole response process obeys the law of conservation of mass and the law of conservation of energy.

a) Conservation of mass:

\[
dm/dt = dm_s/dt - dm_l/dt \quad (1)
\]

Where: \( m \) is the net generated mass of steam in the containment vessel; \( m_s \) is the steam mass generated by core heating; \( m_l \) is the condensation quality of the inner wall of the containment.

\[
dm_s/dt = dQ_s/dt \cdot 1/\Delta H \quad (2)
\]

Where, \( Q_s \) is the decay heat released in the containment vessel; \( \Delta H \) is the enthalpy difference between water at 100°C and steam at 100°C.

\[
dm_l/dt = dQ_l/dt \cdot 1/\Delta H \quad (3)
\]

Where, \( Q_l \) is the heat released by condensation of water vapor inside the containment on the containment wall.

b) Conservation of energy

Heat from the condensation of water vapor is transferred through the containment wall to the water inside the containment jacket. The first stage mainly simulates the process of the water inside the shield jacket rising from the initial temperature of 40°C to 100°C, which can be conservatively considered as a natural convection process:

\[
dQ_h/dt = KA(T_f1 - T_f2) = mc(T_f1 - T_f2) \quad (4)
\]

\[
dQ_h = dQ_l \quad (5)
\]

\[
K = 1/(1/h_1 + \delta / \lambda + 1/h_2) \quad (6)
\]

Where, \( Q_h \) is the heat exchange between the water vapor in the containment vessel and the shielding jacket; \( A \) is the effective heat exchange area of the containment vessel; \( T_f1 \) is the temperature in the containment vessel; \( T_f2 \) is the temperature in the shielded water jacket; \( T_f1 \) is the temperature at
the next moment in the shielding jacket; $K$ is the total heat transfer coefficient; $h_1$ is the heat transfer coefficient of the steel wall inside the containment; $\delta$ is the thickness of the inner wall of the containment vessel; $\lambda$ is the thermal conductivity of the inner wall of the containment; $h_2$ is the heat transfer coefficient in the containment shield water jacket.

When calculating the heat transfer coefficient in the shielded water jacket, the relation involved is as follows [2]:

$$h_2 = \frac{Nu \lambda}{L} \quad (7)$$

$$Nu = 0.13 \cdot (Gr \cdot Pr)^{\frac{1}{3}} \quad (8)$$

$$Gr = \frac{g \gamma \Delta t H^3}{\nu^2} \quad (9)$$

$$\frac{dQh}{dt} = A(T_f1 - TW_2)/(1/h_1 + \delta/\lambda) = A(T_f1 - T_f2)/(1/h_1 + \delta/\lambda + 1/h_2) \quad (10)$$

$$\Delta t = TW_2 - T_f2 \quad (11)$$

Where: $Nu$ is the Nusselt number; $H$ is the height of the containment vessel; $Gr$ is Grashof number; $\gamma$ is the coefficient of volume expansion; $\nu$ is kinematic viscosity; $T_{w2}$ is the temperature of the outer wall of the containment.

The second stage mainly simulates the process of water boiling at 100°C into water vapor at 100°C in the shielding water jacket, which belongs to the boiling heat transfer process in the shielding water jacket:

$$\frac{dQh}{dt} = KA(T_f1 - TW_2) = \Delta m \Delta H \quad (12)$$

Where, $\Delta m$ is the phase change mass of water.

The second stage is different from the first stage in two aspects:

a) There is less water in the shielding water jacket, so the heat exchange area is reduced;

b) The heat transfer in the shielding water jacket changes from natural convection to boiling heat transfer.

4. Simulation and Analysis

4.1. Simulation of Temperature and Pressure in the Containment at a Certain Time

The relevant design input parameters are shown in Table 1.

It is conservatively assumed that the initial pressure in the containment vessel is 1.1 bar and the initial temperature is 40°C. At the time of the 1800s after the LOCA, the suppression pool system can meet the pressure in the containment vessel less than 5 bar.

By iteratively solving the pressure values of each containment, the corresponding partial pressure of non-condensable gas and partial pressure of steam in the containment can be obtained. At the same time, the LAPWS-IF97 physical calculation program is used to obtain the relevant data of partial pressure of steam $P$ and dew point temperature of steam $T$, and the relational expression is obtained by fitting:

$$YT = 99.726X0.2647 \quad (13)$$

| Numble | Relevant design input parameters | Parameter values |
|--------|----------------------------------|-----------------|
| 1      | Parameter numerical containment initial pressure /bar | 1.1 |
| 2      | Initial temperature in containment /°C | 40 |
| 3      | System start time /s | 1800 |
| 4      | LOCA post accident containment pressure /bar | 5 |
| 5      | Free volume in containment /m$^3$ | 600 |
| 6      | Shielding jacket temperature /°C | 40 |
Where: $Y_T$ is the value of vapor dew point temperature $T$; $X$ is the value of the partial pressure $P$ of the vapor.

4.2. Simulation Calculation of Heat Transfer Area At a Certain Time

Stage 1: the water in the shielding water jacket changes from 40°C to 100°C, with the heat exchange area unchanged. The whole heat exchange area is divided into the head part and the vertical cylinder part, which is calculated conservatively, ignoring the heat exchange area of the head part.

The second stage: the water inside the shield changes from the boiling phase of water at 100°C to the steam at 100°C. The volume of water is decreasing, so is the heat exchange area. Then the relation between the heat exchange area $A_n$ at one time and the heat exchange area $A_{n+1}$ at the next time can be obtained:

$$A_{n+1} = A_n - \frac{[2R_1/(\rho R_2^2 - \rho R_1^2)]}{\text{d}m/\text{d}t} \ (14)$$

Where, $\rho$ is the density of water; $R_1$ is the inner radius of the shielding jacket; $R_2$ is the outer radius of the shielding jacket.

4.3. Calculation of the Total Heat Transfer Coefficient At a Certain Time

By iteratively solving the pressure values of each containment, the corresponding partial pressure of air and steam in the containment can be obtained. Meanwhile, according to the relationship of Uchida heat transfer coefficient [3][4], the relationship between pressure $P_Z$ in the containment and heat transfer coefficient $h$ on the inner wall of the containment can be obtained as follows:

$$YZ = -1.7473X_1^2 + 188.31X_1 - 211.6 \ (15)$$

Where: $Y_Z$ is the value of pressure $P_Z$ in the containment; $X_1$ is the value of heat transfer coefficient $h_1$ on the inner wall of the containment.

4.4. Net Steam Production in the Containment At a Certain Time

The relation between known shutdown time $t$ and decay heat $Q_s$ is as follows:

$$Y_s = -18.09X_t - 0.278 \ (16)$$

Where: $Y_s$ is the value of decay heat $Q_s$; $X_t$ is the value of the shutdown time.

According to the calculations in sections 3.1 to 3.3 and combined with equations (1) to (12), the net steam production in the containment at a certain time can be obtained.

4.5. Thermal Response Analysis At the Next Moment

Equation of state for ideal gas [5]:

$$PV = nRT \ (17)$$

The relationship between the pressure change of containment steam and temperature and mass is as follows:

$$P_{n+1} = (P_n + \Delta mRT/MV)(T_n/T_{n-1}) \ (18)$$

Where, $T_n$ represents the temperature at the previous time, and $T_{n-1}$ represents the temperature at the previous time.

According to the vapor partial pressure at the next time, the corresponding vapor dew point temperature can be obtained. The partial pressure of the non-condensable gas is only related to temperature, so the partial pressure of the non-condensable gas at the next moment $P_{k(n+1)}$ is related to the partial pressure of the non-condensable gas at the previous moment $P_{kn}$ is as follows:

$$P_{k(n+1)} = P_{kn} \cdot T_{n+1}/T_n \ (19)$$

Then the pressure in the containment at the next moment:
Pz(n+1) = Pk(n+1) + Pn+1 (20)

After the pressure inside the containment at the next moment is obtained, the heat transfer coefficient of the inner wall of the containment at the next moment can be obtained according to formula (15), and the total heat transfer coefficient can be obtained according to formula (6). According to formula (4), the temperature in the shielded water jacket at the next moment can be obtained. Similarly, relevant parameters are simulated and calculated to obtain the values of all parameters at the next moment. By analogy, the thermal response process in the containment can be obtained based on LOCA of the passive thermal conduction system of the containment.

5. Analysis Curve of Simulation Results
Figure 3 Shows the Pressure and Temperature Time h in the Containment after the Passive Heat Extraction System is put into Operation.

As can be seen from figure 2 and figure 3, after the passive heat extraction system of the containment was put into operation, the temperature and pressure in the containment rapidly dropped. After 13911s, that is 3.86h, the water in the shielding water jacket reached 100℃, and then entered the second stage of heat exchange, and the temperature and pressure continued to decrease. The passive heat extraction system of the containment can ensure that the temperature and pressure value in the containment is within the design range within 72h. After the accident, the integrity of the third barrier of the containment can be guaranteed.

![Figure 2 Containment Vessel Pressure Changes](image)

![Figure 3. Containment Vessel Temperature Changes.](image)
6. Conclusion

In this paper, a thermal response analysis method for the passive heat extraction system of containment is proposed. This method is used to analyze the medium and long term thermal response of the containment system based on passive heat. The analysis results show that the system can meet the long-term requirements of the accident, that is, the integrity of the third barrier of the containment after the accident is guaranteed, avoiding the large release of radionuclides into the external environment after extreme working conditions.

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