Study on Application of Phase Change Material for passive containment cooling

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1. Introduction

After the Fukushima accident, the importance of passive system is increased. As a main passive safety system, Passive Containment Cooling System (PCCS), which utilizes natural phenomena to remove the heat released from the reactor, is applied to the advanced pressurized water reactor (APWR).

To increase the efficiency of passive cooling, additional cooling method using Phase Change Material (PCM) is suggested in this paper. PCM has a good potential because it stores heat energy as a form of latent heat during phase change. For containment using PCMs, there are many advantages. First, maintenance expenditure is free because PCM melts at accident conditions only. Second, it is a simple system and it is not necessary to penetrate the containment wall. The risk of radioactive material release is decreased substantially. Third, it is possible to install for the existing nuclear power plants under operation. Fourth, it can be used alone or as a passive auxiliary cooling system with other PCCS.

2. Methods

In this section the selection of suitable candidate materials as PCCS and the calculation process of the approximate amounts required to meet the PCCS criteria are described.

2.1 Selection of PCM candidates

To evaluate the applicability of PCM to PCCS, appropriate PCM candidates were selected first. On the basis of the thermophysical properties of PCMs, all of candidates were classified under the following criteria listed in Table I. Major characteristics of energy storage materials pointed out by B.Zalba is referred. The melting points are chosen to be near the temperature which can be arrived during accident conditions. Commercial PCMs available in the market is considered.

2.2 Calculation for the amount of PCM

The minimum mass and volume of PCM are necessary to keep the final containment pressure below design limit. Thermodynamic calculation is first performed to calculate the required minimum mass and volume of PCM condenser. The calculation method is suggested by Todreas et al [2].

Thermodynamic system, as shown in Fig. 1, is composed of three subsystems: mass of air in containment(m_a), water initially in the primary system depending on rupture assumption(m_{wp}), and mass of PCM in the PCM condenser (m_{pcm}).

The reference reactor is APR 1400 (Advanced Power Reactor 1400). The initial and final conditions for APR 1400 is summarized in Table II. From the general PCCS design criteria, the total heat absorption of the PCCS is set as the decay heat after 5 minutes of shutdown. Also, the integrity of the containment should be maintained for at least 72 hours after 5minutes of shutdown. The decay energy is obtained from the tabular data from PSAR (5min ~ 7hrs) and decay heat curve of reactor for long term heat. Assumptions for the theoretical model is made and shown below.

Table I: Criteria for PCM to apply to the containment [1]

	Criteria	Remark
1	Thermal properties	• Phase change temperature near 49~70°C (accident condition) to cooling containment in accident • High latent heat • High thermal conductivity
2	Physical properties	• High density
3	Chemical properties	• Stability • Non-toxic, non-flammable, non-polluting
4	Economic properties	• Cheap and abundant

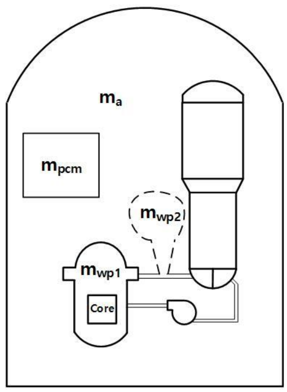

Fig. 1. Schematic diagram of thermodynamic system in PWR

Table II: Initial and final conditions for the calculation

Conditions	
Decay energy	623×10^9 MJ
Initial containment pressure	1.013×10^5 Pa
Initial containment temperature	27 °C
Initial primary system pressure	15.5 MPa
Total free volume of containment	8.86×10^4 m^3
Final containment pressure	0.4 MPa

Assumptions

- The final state is after the completion of the blowdown process.
- Final conditions are defined as the state of pressure equilibrium between the contents of the containment vessel and the primary system.
- The water vapor and liquid exist at the partial pressure of the saturated water vapor.
- Potential and kinetic energy effects are neglected.
- Neglect the initial volume of the PCM.
- Heat transfer to the containment is assumed as the total heat transferred, not the heat transfer rate.
- The final temperature of PCM is the same to that of containment.
- The PCM is a homogeneous isotropic material.

The conservation equation of energy is calculated by following equations.

$$m_{wp}(u_{wp2} - u_{wp1}) + m_a C_{va}(T_2 - T_1) + m_{pcm}\Delta u_{pcm} = Q_{decay}$$

In this equation, the unknowns are the final specific internal energy of water (u_{wp2}), final containment temperature (T_2), the mass of the PCM (m_{pcm}), and the difference of internal energy of PCM (Δu_{pcm}).

The total pressure is determined from Dalton's law of partial pressures. The partial pressure of water is the saturation pressure of the system at the final state. The partial pressure of air can be calculated with the ideal gas law. The following equations are solved iteratively then the final temperature (T_2) is calculated.

$$P_2 = P_{w2} + P_{a2} = p_{sat}(T_2) + \frac{m_a R_a T_2}{V_c}$$

The internal energy of PCM is obtained from the latent heat and sensible heat.

$$\Delta u_{pcm} = C_{pcm,s}(T_m - T_{pcm1}) + u_{fus} + C_{pcm}(T_{pcm2} - T_m)$$

Finally, the mass of PCM is calculated from the conversation equation of energy.

$$m_{pcm} = \frac{Q_{decay} - m_{wp}(u_{wp2} - u_{wp1}) - m_a C_{va}(T_2 - T_1)}{\Delta u_{pcm}}$$

Although the initial volume of PCM was not considered initially, the calculation was repeated with considering the PCM mass and the converged results are obtained.

3. Results

The results of various PCMs were compared to select the most suitable PCM among the candidate materials. The case of ice was also considered for comparison with the results of PCM. The required minimum mass and volume of PCM candidates are shown graphically in Fig. 3.

From the results, the candidate with the minimum mass by 10,847 ton is A58H. Otherwise, Climsel C70, which has higher density than that of A58H, satisfies the minimum volume of 7,919 m^3. It is about 10% of the total free volume in the containment. In terms of containment safety, it is important to have more free volume to minimize the pressure and temperature peak. As a result, Climsel C70 is considered as the most suitable material for the PCM condenser.

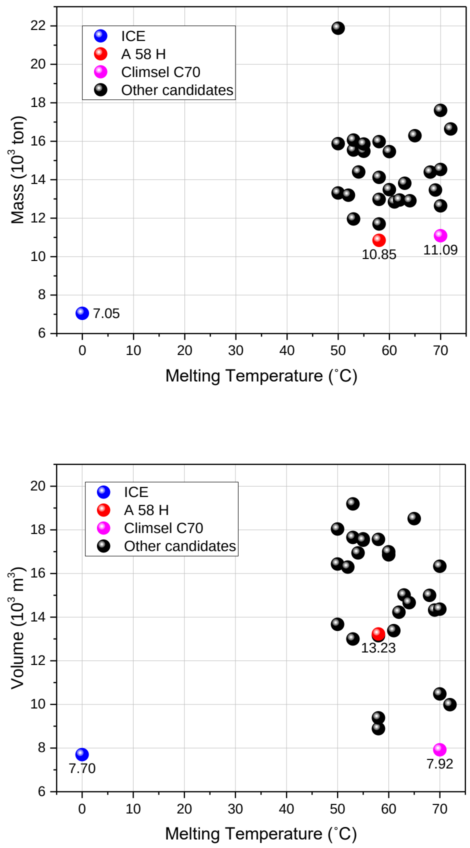

Fig. 3. The required minimum mass and volume of PCM candidates.

3. Summary and Further Works

The concept of a PCM condenser for a PCCS has been proposed. To evaluate the application of PCM for the containment passive cooling in APR 1400, PCM candidates are selected in the first step. Thermodynamic calculation was performed to determine the amount of PCM required for PCM condenser. As a result, Climsel C70, which satisfies the minimum volume, was considered as the most suitable material.

As the next step, a numerical study will be conducted by using developed CAP (nuclear Containment Analysis Package) code to analyze the cooling performance of the

PCM. The target heat transfer rate, which satisfies the PCCS criteria, will be estimated.

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