Evaluation of PCM Condenser for Containment Passive Cooling Using CAP

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1. Introduction

KAIST research team proposed a new safety system concept that has the capability of passively cooling containment by using phase change material (PCM) shown in Fig 1 [1]. This proposed PCM condenser has the advantage not limited to an application to existing power plants. In this study, a preliminary design is performed to evaluate whether the PCM condenser satisfies sufficient cooling performance in a hypothetical accident. Shin-Kori unit 3 is selected as a reference plant, which is one of the recently constructed and operating nuclear power plants. The performance of the PCM condenser compared to that of the existing spray system is evaluated. The accident analysis is performed with CAP (nuclear containment analysis package) code version 2.21. CAP is a lumped-parameter (LP) code developed by the Korean industrial consortium for the analysis of thermal-hydraulic behavior in the containment [2].

(a)

(b)

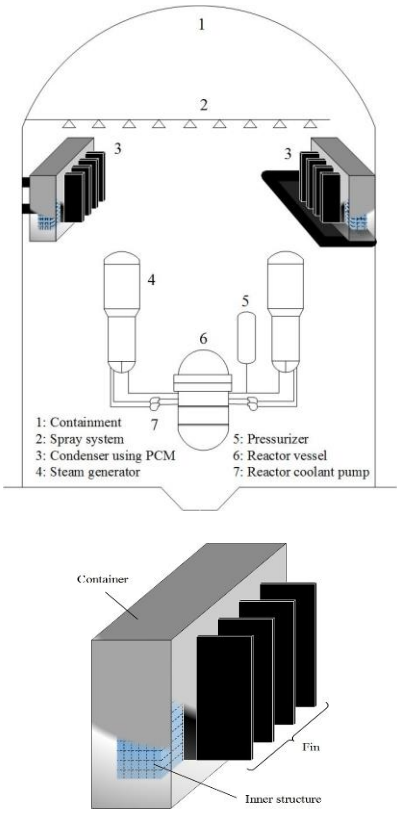

Fig. 1. Configuration of PCM-based PCCS (a) within the containment, and (b) PCM steam condenser module [1].

2. Methods

To evaluate the performance of the PCM condenser, a reference accident should be determined. The most severe accident is selected for the scenario, which is a double-ended discharge leg slot break (DEDLSB) with 0.1921 m^2 break size and maximum SIS capability [3]. Table I shows the assumed initial conditions [4]. It is also assumed that PCM-based PCCS is solid but has a heat capacity profile with temperature simulating the latent heat. Modeling methods are validated from the previous study [3].

TABLE I: Initial condition applied to accident analysis

Parameter		Initial value
Rx building	temperature	48.9°C
	pressure	0.1165MPa
	relative humidity	5%
Spray system	temperature	10°C
	delay time	110sec

3. Preliminary Design

To preliminarily design the PCM condenser, safety standards for containment building of the reference plant were investigated as shown in Table II [3]. Domestic and foreign design requirements related to passive containment cooling systems also were reviewed and summarized in Table II [4]. Each PCCS had its own design requirements. For evaluating the performance of the PCM condenser, these requirements are also compared.

Table II. Reactor containment building safety standards & various PCCSs' design requirements

Criteria	Safety standard
Rx building over-pressure protection	less than 0.52 MPa
Rx building over-heating protection	less than 143.3 ℃
Criteria	**Requirements**
Heat removal ability (APR+ PCCS)	absorb more heat than decay heat generated from 5min to 72hr after shutdown.
Rx building pressure stabilization (APR1400 Spray)	reduce pressure to less than 50 % of peak value

The design criteria of the PCM condenser were determined as shown in Table III by the case study with reactor building safety standards [3]. Table IV shows the design values of the PCM condenser based on these design criteria.

TABLE III: Established design criteria

Design parameter	Design Criteria
Total volume of PCM condenser	less than 25% of free volume of containment building
Melting point of PCM	less than 78 ℃
Effective thermal conductivity	larger than 6.25 W/m-K
Heat transfer area	larger than 10,000 m^2
Product of k_{eff} and heat transfer area	larger than 125 kW/K

TABLE IV: Design value of the PCM condenser

Design parameter	Design Value
Total volume of PCM condenser	25%
Phase Change Material (PCM)	PureTemp58
Effective thermal conductivity	15 W/m-K
Heat transfer area	20,000 m^2
Product of k_{eff} and heat transfer area	300 kW/K

4. PCM Condenser Performance Evaluation

For the DEDLSB accident scenario, safety analyses are performed for a total of four cases, a combination of spray system single failure or total failure and with PCM condenser or without PCM condenser. Since the spray system is operated actively, the single failure case is compared with the PCM condenser. The pressure and temperature graphs for the four cases are shown in Fig. 2. Safety analysis is performed for 72 hours because it is assumed that action is possible from the outside three days after the accident initiation in general. Without any safety system (TF spray & no PCM case), pressure and temperature continue to increase beyond the range of the graph due to the absence of the cooling source. On the other hand, in the case of having the PCM condenser, pressure rises slightly faster during the blowdown period (~19 second) than the others. This is because the free volume of containment building is decreased as the PCM condenser occupies the volume and the pressure of containment building responds more quickly. However, the pressure and temperature of the containment building are stabilized faster after the blow-down period for the cases with the PCM condenser than the others. In the case of TF spray & PCM, the pressure slightly increases from 50 hours of the accident initiation, but the final pressure and temperature of the containment building do not differ significantly between the two cases at 72 hours after accident initiation (TF spray & PCM and SF spray & no PCM). In other words, the PCM condenser has the cooling capability as much as a single spray system. In conclusion, the PCM condenser has the ability to stabilize the internal pressure of the containment building much faster than the spray system, although it has some drawbacks of a slightly quicker response in pressure during the blow-down period.

Compared with the design requirements of domestic and foreign PCCS mentioned in Table II, the PCM condenser has sufficient performance. The PCM condenser achieves the design requirement of the spray system in APR1400, which reduces pressure to less than half of peak without other safety system. To confirm that the PCM condenser satisfies the PCCS of APR+, decay heat and absorbed heat from containment building to PCM condenser is calculated. Fig. 3 shows the amount of heat absorbed to the PCM condenser and the PCM condenser absorbs approximately 6.5 TJ during 72 hours. The calculated decay heat generated 5 min to 72 hours after shutdown is approximately 7 TJ, when Patterson-Schlitz's empirical decay heat curve of ANS-5 is used with the assumption of 3 years operation time and 4000 MWth. Although the PCM condenser does not fully meet the design requirement of APR+ PCCS, it can be still suggested that the PCM condenser can absorb heat almost similar amount of decay heat without any external heat sink.

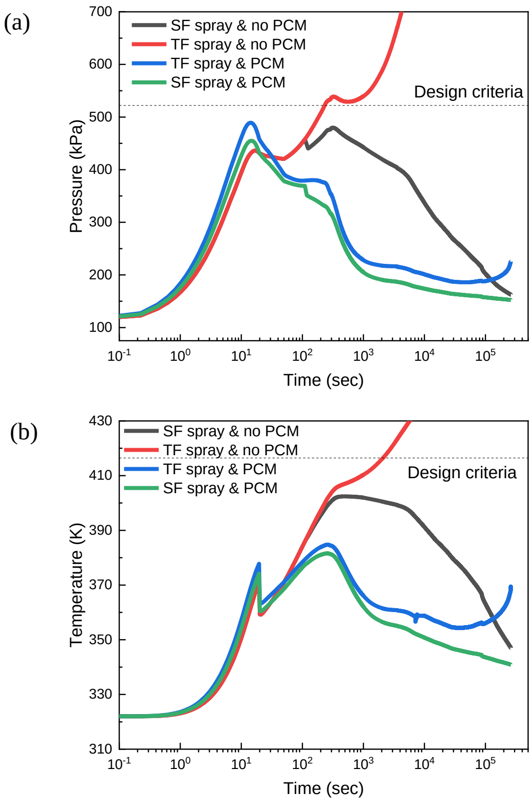

Fig. 2. Containment building (a) pressures and (b) inner wall temperature trends during 72 hours after accident initiation depending on safety system activations.

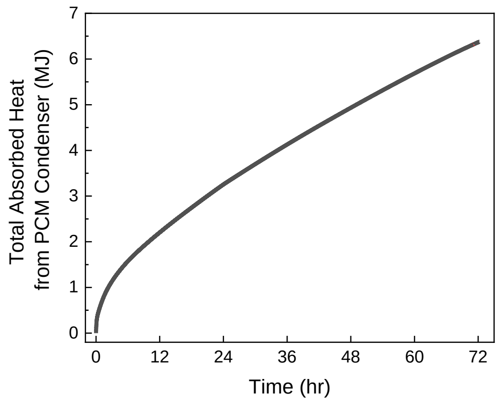

Fig. 3. Absorbed heat from PCM condenser.

4. Conclusions

The performance of the PCM condenser, which is a new concept of containment passive safety system, was preliminarily designed and evaluated. The PCM condenser cools the containment building with a similar ability to the existing active single containment spray system, so the proposed PCM condenser can be sufficiently utilized for cooling containment passively for the operating nuclear reactor.

ACKNOWLEDGEMENT

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