# Preliminary design of PCM-based PCCS by using CAP code

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## 1. Introduction

The necessity of Passive Containment Cooling Systems (PCCSs) has been emphasized since the Fukushima Daiichi nuclear power plant accident. In response, the KAIST research team proposed a new PCCS concept using phase change material (PCM) as shown in Fig 1 [1]. In order to design a PCM-based PCCS, design parameters should be defined, which can be a reference point whether the safety standards are satisfied or not under hypothetical accidents. In this study, several design parameters are defined, and a case study of accident is performed to establish criteria for each design parameters. The accident analysis is performed with CAP (nuclear containment analysis pack) code version 2.21. CAP is a lumped-parameter (LP) code developed by Korean industrial consortium for the analysis of thermal hydraulic behavior in the containment [2].

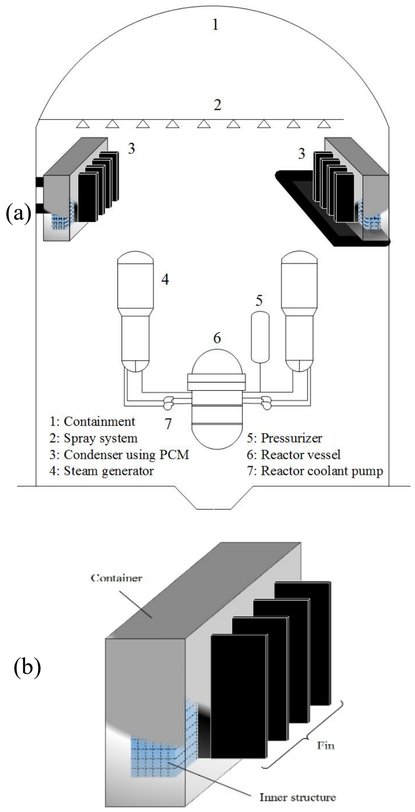



Fig. 1. Configuration of PCM-based PCCS (a) within the containment, and (b) PCM steam condenser module [1].

## 2. Selection of hypothetical accident

In order to perform an evaluation for each design parameter, a reference accident should be determined. During a loss of coolant accident (LOCA), the amount of energy released inside the containment building is the largest among many design basis accidents (DBAs), so that LOCA is selected as the accident scenario to define design criteria. Since most of the reflood fluid does not pass through a steam generator prior to release to the containment in the case of hot leg break, only the case of cold leg break is analyzed. This is because for the case of cold leg break the residual secondary system energy in the steam generator is more rapidly released than the case of hot leg break during or after reflood phase. The break position is set to discharge leg slot (DEDLSB) or suction leg slot (DESLSB) with 0.1921 $m^2$ break size and maximum SIS capability. For the case of DESLSB and DEDLSB, maximum pressure and temperature (Max PT) analysis is preliminarily performed. Among the analyzed cases, an accident with the most severity is selected for the scenario to judge the design criteria. Mass and energy release are referred from FSAR of Shin-Kori unit 3-4, which is calculated by CEFLASH-4A or FLOOD3.

### *2.1. Assumptions for accident analysis*

Table I shows the assumed initial conditions for the reactor containment building. Initial pressure and temperature are set to be the maximum value and humidity is set to be the minimum value at normal operating condition. The source of spray water temperature is set to 10$^o$C and delay time of spray pump is set to 110 seconds after containment pressure reaches the high-high pressure setpoint. In the analysis, it is assumed that a single failure of one of the two spray systems for conservatism. It is also assumed that PCM-based PCCS is a solid but has a heat capacity profile with temperature simulating the latent heat. More details and validation of modeling methods of PCM can be found in previous study [3].

TABLE I: Initial condition applied to accident analysis

| Parameter | | Initial value |
|---|---|---|
| Rx building | temperature | 48.9$^o$C |
| | pressure | 0.1165MPa |
| | relative humidity | 5% |
| Spray system | temperature | 10$^o$C |
| | delay time | 110sec |

*2.2. Selection of design basis accident*

Figs. 2 and 3 show pressure and temperature changes for the case of DEDLSB and DESLSB, respectively. Fig 4 shows the change of pressure and accident sequence. In Figs 2 and 3, it can be confirmed that the DEDLSB is a more serious accident than the DESLSB. While the consequence of DESLSB has already been mitigated at the end of post reflood, the containment pressure still rises after the end of post reflood in the DEDLSB case. Moreover, the maximum temperature and pressure of DEDLSB is larger than those of DESLSB, so the analyzed accident for the PCCS evaluation is determined to be DEDLSB.

(a)

(b)

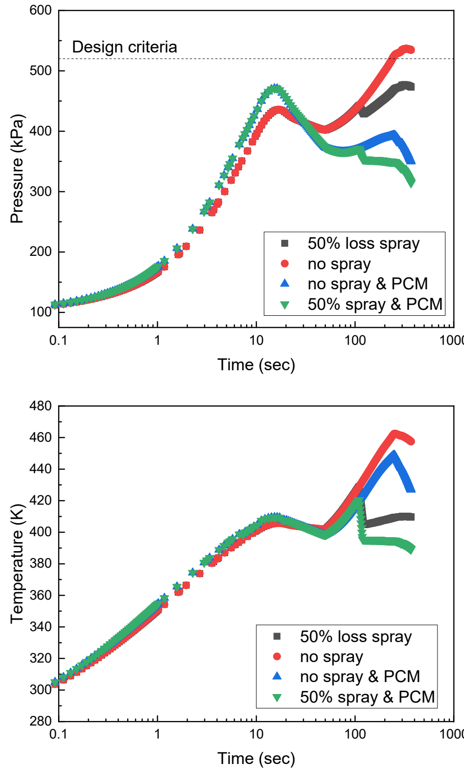
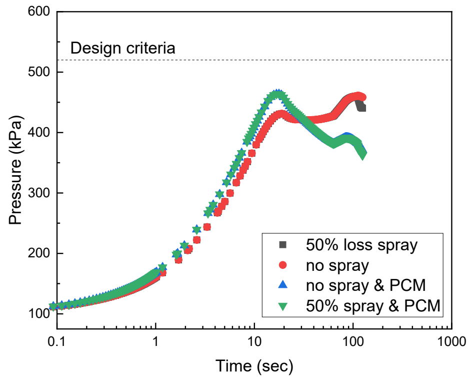



Fig. 2. In the case of DEDLSB, (a) pressure and (b) temperature change for the several cases.

(a)




(b)

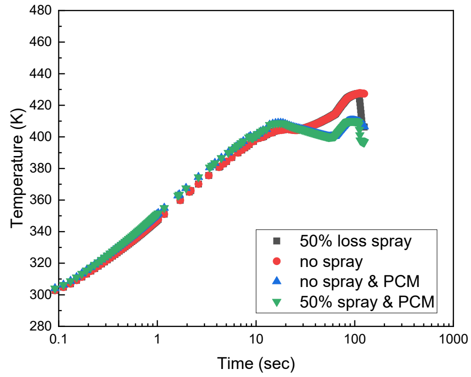



Fig. 3. In the case of DESLSB (a) pressure and (b) temperature change for the several cases.

(a)

(b)

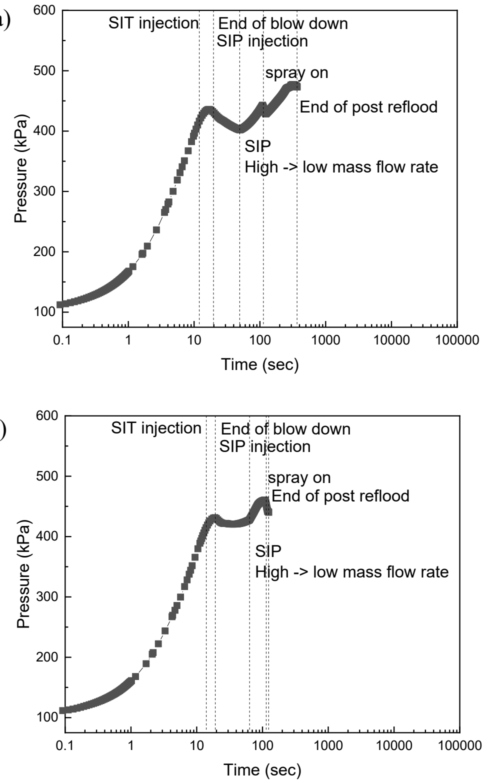



Fig. 4. Accident sequence with pressure change (a) DEDLSB (b) DESLSB.

## 3. Design criteria

There are many parameters that affect the performance of PCM-based PCCS. The following variables are selected for design parameters: total volume of PCM-based PCCS, melting point of PCM, effective thermal conductivity of PCM-based PCCS, heat transfer area of PCM-based PCCS, multiplication factor of the effective thermal conductivity and heat transfer area, and total absorbed heat of PCM-based PCCS.

The design criteria can be established by checking whether case study results mitigate the accidents or not. That is, it is confirmed that the containment building satisfies the safety standards while changing the values of each design parameter. Long-term cooling analysis is conducted for DEDLSB and it is considered that the accident is mitigated unless the safety standards are violated within 72 hours. The safety standards are defined in Table II [3].

TABLE II: Reactor containment building safety stanards

| Criteria | Safety standard |
|---|---|
| Rx building overpressure protection | less than 0.52 MPa |
| Rx building overheating protection | less than 160 °C |

### *3.1. With respect to free volume*

Among many design parameters, the effect of the total volume of PCM-based PCCS is evaluated. Since the PCM-based PCCS is proposed to be installed in the containment building, the containment free volume reduction has to be also estimated. In order to estimate the effect of total volume of PCM-based PCCS, case study of various free volume reductions is analyzed without total volume of PCM-based PCCS. This is to focus on the effect of total volume of PCM-based PCCS, not for the thermal performance.

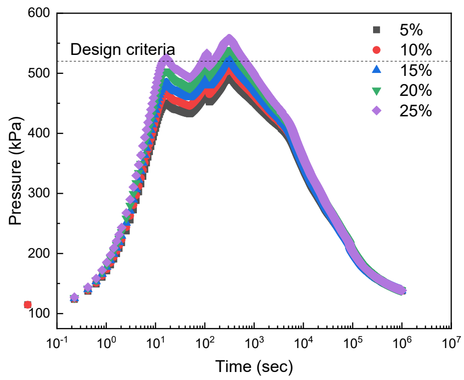



Fig. 5. Pressure changing in the several cases having free volume deduction.

With respect to 5, 10, 15, 20, 25% free volume reduction, pressure of containment building is calculated by CAP, which is shown in Fig 5. As a result, when the free volume reduction is less than 15%, the pressure of containment building can be maintained under overpressure criterion, 0.52 MPa. That is, the design criterion of total volume of PCM-based PCCS is determined to be less than 15% of the free volume of the containment building.

### *3.2. With respect to thermal performance*

The total amount of heat absorbed by PCM-based PCCS is affected by many parameters such as the thermal conductivity, heat transfer area, melting point, latent heat, etc. Among them, the effect on the melting point of PCM, effective thermal conductivity and heat transfer area of PCM-based PCCS is evaluated. The analysis is performed by changing the three pairs of variables. Test matrix is shown in Table III. It is assumed that amount of PCM is the same, and the density, latent heat, and specific heat of PCM is the same in all of the cases.

TABLE III: Test matric to evaluate effect of absorbed heat

| Parameter | Test values | | | | |
|---|---|---|---|---|---|
| melting point (°C) | 58 | 78 | 98 | 118 | |
| effective thermal conductivity (W/m-K) | 0.25 | 6.25 | 12.5 | 18.75 | 25 |
| heat transfer area ($m^2$) | 5,000 | 10,000 | 15,000 | 20,000 | |
| latent heat (J/kg) | 340,000 | | | | |
| specific heat (J/kg-K) | 2700 | | | | |

Fig 6 shows performance maps with respect to effective thermal conductivity and heat transfer area at a fixed melting point. This is a method previously used by Ko [4] to evaluate the performance of PCM-based PCCS. In Fig 6, there is no difference between the cases of melting point of 58°C and 78°C, but when the melting point of PCM becomes 98°C, the performance of PCM-based PCCS degrades and when becoming 118°C, the thermal performance is very unsatisfactory. As a result, the criterion of the melting point of PCM is determined to be 78°C or less.

As shown in Fig 6, the accident cannot be mitigated when the effective thermal conductivity is less than 6.25W/m-K or the heat transfer area is less than 10,000$m^2$ in all cases. Therefore, the criteria are established lager than 6.25W/m-K for the effective thermal conductivity and larger than 10,000$m^2$ for the heat transfer area. It is also observed that an accident is mitigated in the diagonal form, so the criterion for the multiply of thermal conductivity and heat transfer area is added. This value is conservatively set to 125kW/K or more.

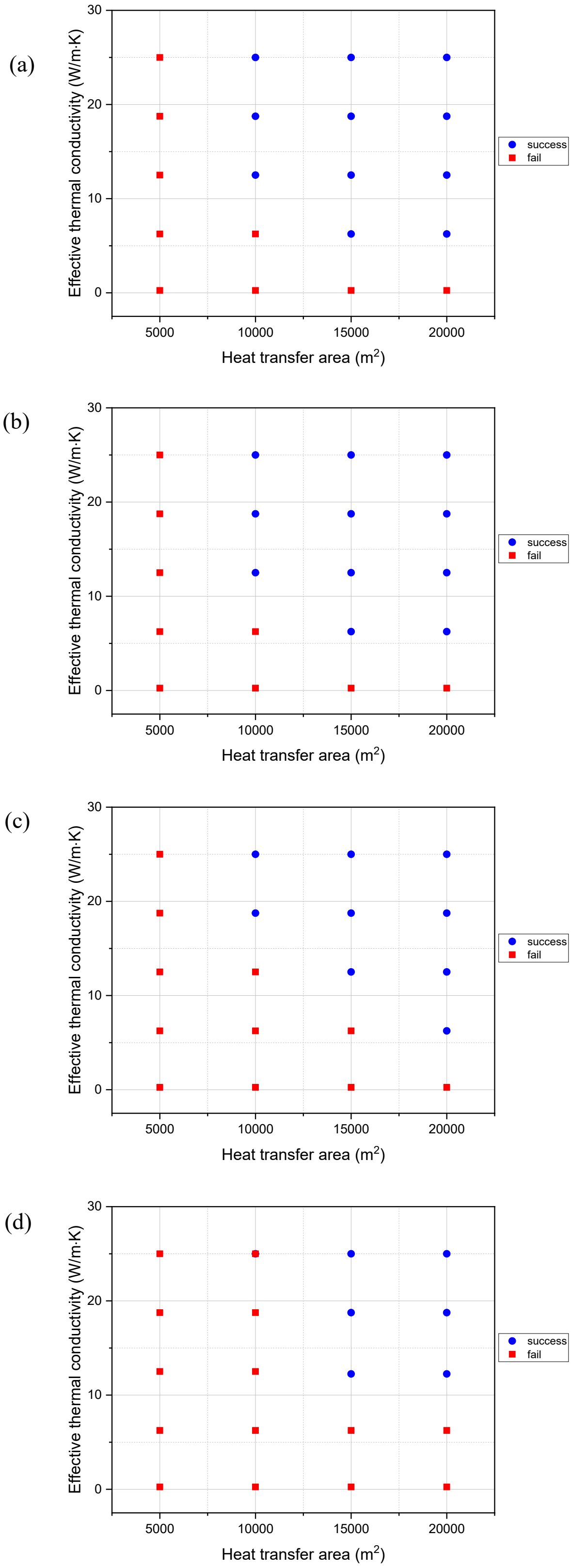



Fig. 6. Performance maps of PCM-based PCCS with melting point of (a) 58$^{o}$C (b) 78$^{o}$C (c) 98$^{o}$C (d) 118$^{o}$C.

Fig 7 shows the total heat absorbed by the PCM-based PCCS from the containment building for all cases of Fig 6.

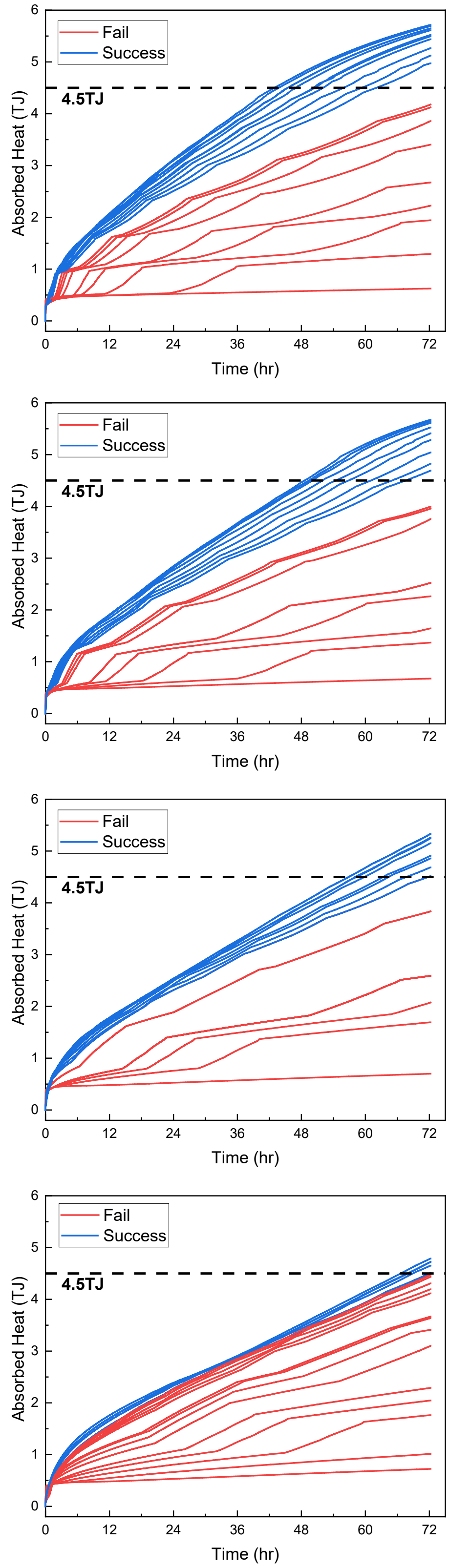



Fig. 7. Total absorbed heat into PCM-based PCCS with melting point of (a) 58$^{o}$C (b) 78$^{o}$C (c) 98$^{o}$C (d) 118$^{o}$C.

In Fig 7, it can be confirmed that the PCM-based PCCS absorbed more than 4.5TJ from the containment building in all cases where the accident is mitigated. Therefore, the criteria for the total absorbed heat of PCM-based PCCS is set to a value larger than or equal to 4.5 TJ. The design criteria for all the design parameters are summarized in Table IV.

TABLE IV: Established design criteria

| **Design parameter** | **Design Criteria** |
|---|---|
| Total volume of PCM-based PCCS | less than 15% 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 |
| Total amount of absorbed heat | larger than 4.5 TJ |

## 4. Conclusions & Further works

KAIST research team proposed a new PCCS concept using PCM. To apply PCM-based PCCS in the containment building, the design criteria of PCM-based PCCS should be established. In this study, design parameters are defined and design criteria are determined by accident analysis with CAP code. The determined design criteria of PCM-based PCCS is summarized in Table IV. By referring to this design criteria, PCM-based PCCS will be designed and evaluated in the future.

## ACKNOWLEDGEMENT

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