CFD Thermal Analysis at the Self-Sealing PCM Placed Liner Plate Panel

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1. Introduction

In the normal case, the nuclear containment building act as the final barrier to block the release of a radioactive material. On the other hand, in the case where the containment liner plate is damaged and there exist some cracks on the concrete, there is a possibility for a radioactive material to be released through the damaged part of the liner plate and cracks on the concrete. The system such as the containment filtered venting system (CFVS) is developed to release the pressure and minimize the release of a radioactive material during the severe accident situation. However, there has been no measure to filter or prevent a radioactive material from escaping through the damaged part of the liner plate and cracks on the concrete.

As the measure to minimize the release of a radioactive material through the damaged containment, the self-sealing strategy using a phase change material (PCM) was suggested by KAIST team [1,2]. In this strategy, the PCM would be set up on the horizontal anchor and be stuck to liner plate panel (Fig. 1). The PCM melts, flows through the crack and finally solidifies in the crack, so it could act as the sealing material (Fig. 2).

For the real application of the self-sealing strategy using the PCM, the amount of the PCM should be decided. At the same time, it should be checked whether the PCM melts or not in suitable time for sealing. Therefore, in this study, the thermal analysis on the PCM placed liner plate panel is conducted using CFD method. The times for the PCM to melt are compared between the finned case and non-finned case, and the suitable thickness of the PCM is suggested.

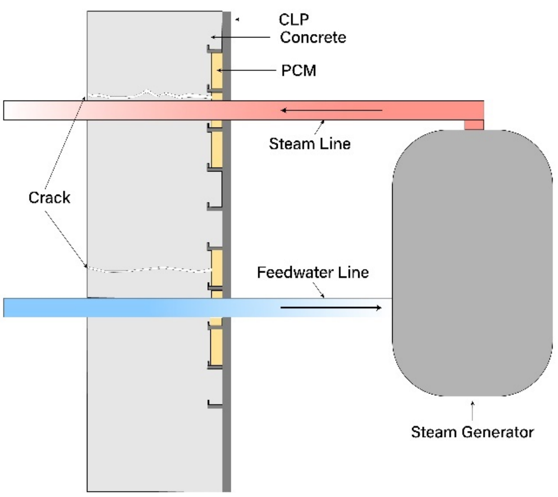


Fig. 1. Diagram of the PCM placed containment

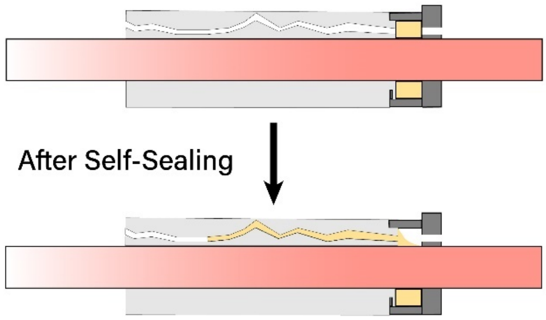


Fig. 2. Example of the self-sealing mechanism

2. Methods and Results

2.1 Geometry and Mesh Modeling

For the CFD program, STAR-CCM+ is used. The analysis is conducted on the single plate panel, which is surrounded by horizontal and vertical anchors (red box in Fig. 3). The constituents are modeled in two dimension. The geometry scene shows the modeled configuration without fins and with fins (Fig. 4). The PCM is placed on the horizontal anchor and stuck to the liner plate. The spacing between horizontal anchors is set up as 1 [m], and the thickness of the PCM is varied from 10 to 40 [mm]. The thickness of the liner plate and the anchor is set up as 8.6 [mm], which is the value of APR1400 [3]. The length of the anchor is set as 127, 67.6 [mm] in x-direction (radial) and in y-direction (axial), respectively [4].

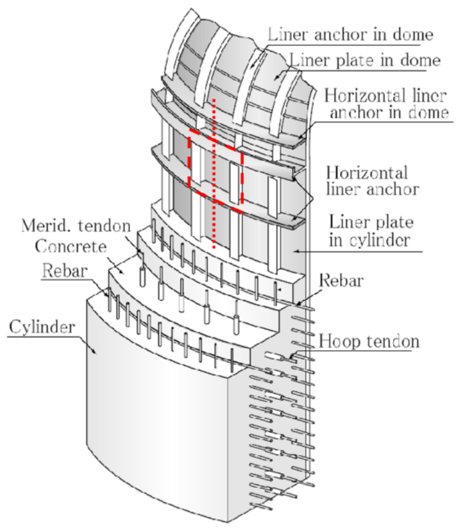


Fig. 3. Analysis object set-up

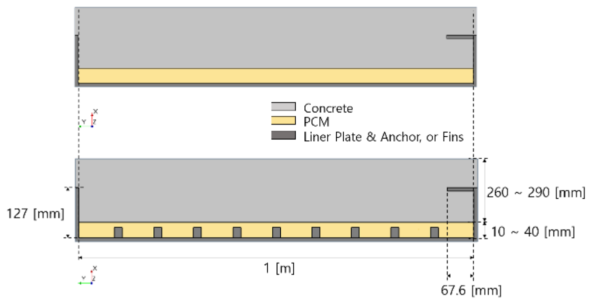


Fig. 4. Geometry scene of the non-finned case (upper) and finned case (lower) (The geometry is 90° rotated in counter-clockwise direction)

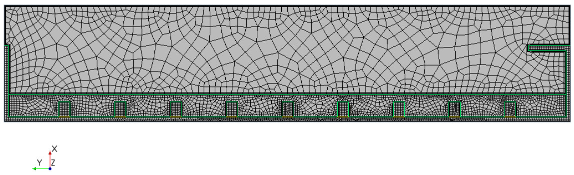


Fig. 5. Mesh scene

2.2 Thermal Hydraulic Models and Properties

Implicit unsteady, two dimensional, and segregated energy model are used in common for both solid and fluid. For the PCM, which can also be in the fluid states, volume of fluid (VOF) model to use the melting-solidification option and segregated flow model are used additionally. The VOF model is a simple multiphase model and it is efficient when each phase is composed of a large structure. The melting of the PCM doesn't make a lot of structures such as bubbles the VOF model is suitable for this simulation.

The thermal properties are shown in table I. It is assumed that the liner plate and the anchor is composed with the same stainless steel. The properties of the concrete and the stainless steel (SUS) in APR1400 are used [3]. A53 from Plusice is used as the example PCM. The melting point of the PCM is 53°C and its latent heat is 155 [kJ/kg].

Table I: Thermal Properties of Materials

	Density $\left[\frac{\text{kg}}{\text{m}^3}\right]$	Thermal conductivity $\left[\frac{\text{W}}{\text{m}\cdot\text{K}}\right]$	Specific Heat $\left[\frac{J}{kg\cdot K}\right]$
Concrete	2242	1.59	879.06
PCM (A53)	910	0.22	2220
SUS	7817	46.38	460.46

2.3 Boundary & Initial Conditions, and Temporal Setting

The most of the heat transfer occurs through the liner plate and the heat transfer at near concrete parts is not significant. Therefore, only the inner side of the liner plate is set up as the convection boundary, and the rest of the boundary is set up as the adiabatic condition. The temperature and the heat transfer coefficient at the inner side follows the transient scenario of the APR1400 during LBLOCA DEDLSB [3], which is the design basis accident for the containment design.

The initial temperature of the liner plate is set as 47°C since the highest operation temperature inside the containment is 48.9°C and the small temperature difference exists between the temperature inside and the liner surface [5]. The temperature of the concrete and the PCM linearly decreases from inside (47°C = 320.15K) to outside (43.8°C = 316.95K) initially.

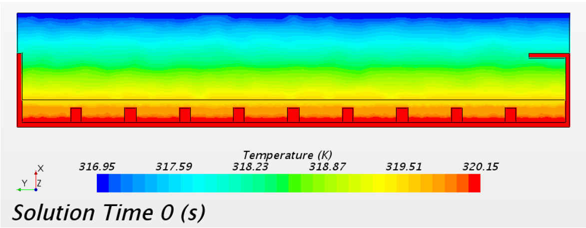


Fig. 6. Initial Temperature Distribution

The time step is set as 0.1 s. This makes the maximum Fourier number smaller than 0.25, which is the stable criteria for the two-dimensional analysis condition (The largest α value is from the SUS properties).

$$\text{Fo} = \frac{\alpha \Delta t}{\Delta x^2} = \frac{(1.2885 \times 10^{-5}) \times 0.1}{(0.004)^2} \cong 0.08 \leq 0.25$$

2.4 Grid Convergence Test

In order to verify the convergence of the solution, the grid convergence test was conducted on some cases. The same case is simulated with the different number of cells. The time for the PCM to totally melt is used to analyze the grid convergence index (GCI) which is commonly used to check a discretization error during CFD analysis [6]. The errors are calculated as 0.002%, 0.023%, 0.016%, and 0.237% for each case number in table II. Therefore, the convergence is verified in this simulation since GCI is small enough in most cases.

Table II: The time for the PCM to melt totally with different number of cells (Cell: number of cells, Melt: time for the PCM to melt totally)

Case No.	Property	N1	N2	N3
1 (Without Fins 1cm)	Cell [-]	16269	7051	2573
	Melt [s]	461.1	460.9	461.2
2 (Without Fins 3cm)	Cell [-]	18936	8126	3864
	Melt [s]	2995	3007.4	3000.6
3 (With Fins 3cm)	Cell [-]	19953	9857	4171
	Melt [s]	2685.5	2677.3	2686.5
4 (With Fins 4cm)	Cell [-]	21435	9831	4567
	Melt [s]	4017.6	4022.9	4031.7

2.5 Result and Discussion

Fig. 7 ~ 13 shows the solid volume fraction variation with various thickness of the PCM, and with or without fins. In order to act as a sealing material, the PCM should melt in suitable time. At the same time, the enough amount of the PCM should be placed to seal the target crack properly. As the placed PCM becomes thicker, the time for the total PCM to melt increases as expected.

In the 10mm thickness case, the total PCM melted in 480s, so the PCM can start to flow in reasonable time. No fin is needed in this thickness case. In the 20mm thickness case, time for the total PCM to melt was the same as 1440s in the non-finned case and the finned case. On the other hand, the difference in time for the total PCM to melt started to be shown from the 30mm thickness case. It took 2700s for the PCM to melt in finned case, but the PCM didn't melt totally in the non-finned case. For the last, in 40mm thickness case, although the PCM didn't melt totally in both cases, the finned case shows evidently wide concrete area that the liquid PCM meets than the non-finned case.

To sum up, if the thickness of the PCM is below 20mm, there would be no big difference between the non-finned case and the finned case. On the other hand, if the thickness of the PCM is larger than 20mm, the fin would widen the contacting area between the PCM and the concrete during the time PCM is melting. Therefore, the PCM can cover more cracks earlier in the finned case than the non-finned case.

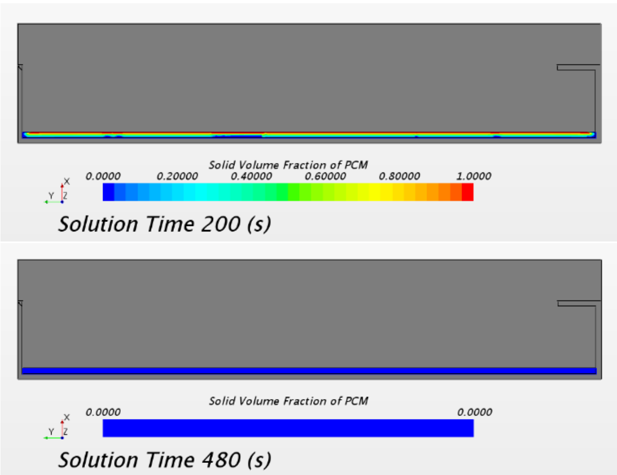
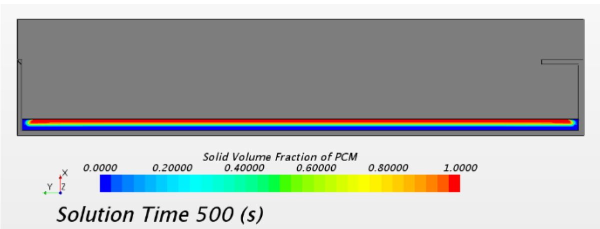


Fig. 7. Solid Volume Variation (Thickness: 10mm, Non-finned)



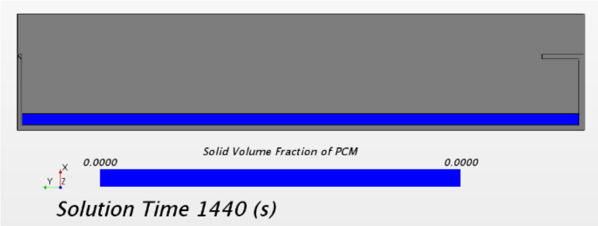


Fig. 8. Solid Volume Variation (Thickness: 20mm, Non-finned)

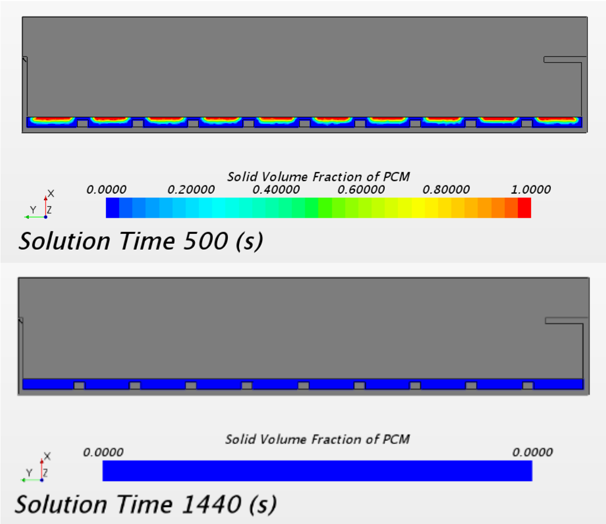


Fig. 9. Solid Volume Variation (Thickness: 20mm, Finned)

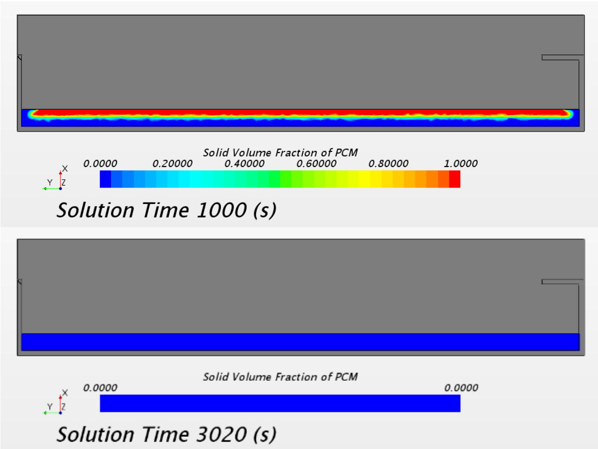
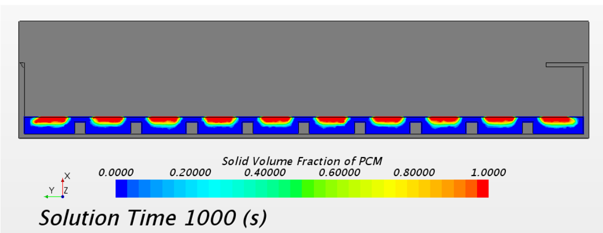


Fig. 10. Solid Volume Variation (Thickness: 30mm, Non-finned)



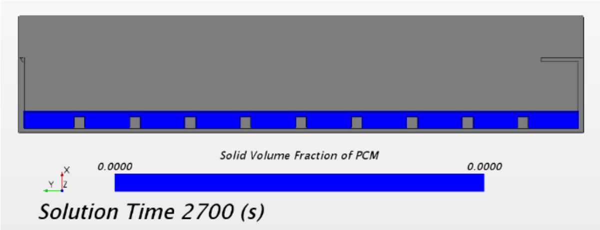


Fig. 11. Solid Volume Variation (Thickness: 30mm, Finned)

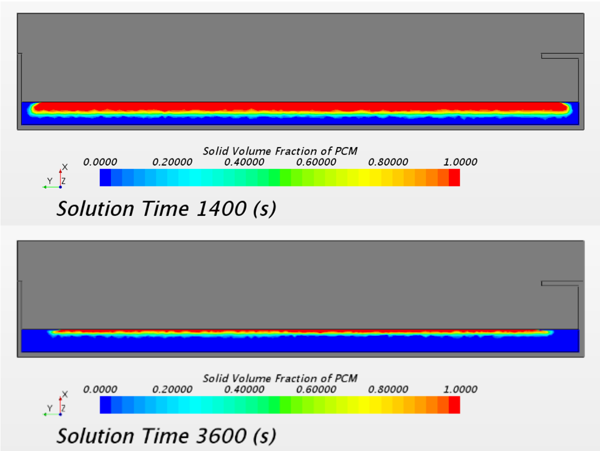


Fig. 12. Solid Volume Variation (Thickness: 40mm, Non-finned)

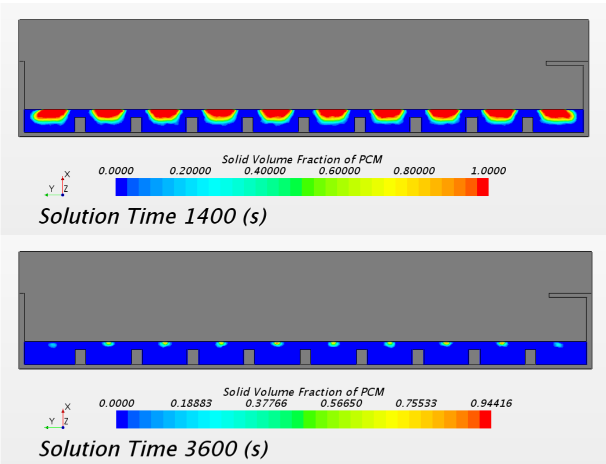


Fig. 13. Solid Volume Variation (Thickness: 30mm, Finned)

3. Conclusions

The self-sealing strategy using the PCM to minimize the release of a radioactive material is introduced. To decide the suitable PCM thickness to place, the thermal analysis using CFD method is conducted. The cases with various PCM thicknesses and with fins or without fins are analyzed.

The amount of the PCM to be placed should be calculated carefully referring to the real nuclear power plant situation. The suitable thickness of the PCM would be decided with the calculated amount of the PCM. It is found that fins would not be needed, if the suitable thickness of the PCM is smaller than 20mm. On the other hand, it is also found that the fin would help to apply the self-sealing PCM to the real nuclear power plant, if the thickness of the PCM is larger than 20mm.

ACKNOWLEDGEMENT

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