Feasibility Study about Self-Sealing Concept Based on the Phase Change Material (PCM) for Nuclear Containment Building

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1. Introduction

The nuclear containment building is built with reinforced concrete to prevent the large release of radioactive materials. As time goes on, concrete deterioration takes place, and some cracks can occur on the concrete. If those cracks are not repaired properly, the possibility for large release of radioactive materials increases. However, an inspection of the concrete and a repair of those cracks are not easy. Therefore, in this study, the self-sealing concept based on the phase change material (PCM) is suggested as the passive measure for repairing cracks, and its feasibility is investigated through the simulation code.

2. Self-Sealing Concept Based on the PCM

The self-healing concept is the widely applied concept for enhancing the integrity of the things by adding the capability to repair the damage itself. The concrete is the representative where the self-sealing concept is used [1]. However, existing self-healing concepts mostly explain about a new concrete mix that has the self-healing capability, so it requires a new design of the building with a new concrete mix.

In contrast, the self-sealing concept, which is suggested in this study, is entirely different from existing self-healing concepts since it does not use any new concrete mix. Instead, this concept uses the PCM to seal a crack. The PCM is a kind of material whose phase changes when the temperature reaches the intended temperature, and which shows a large phase change enthalpy. In self-sealing concept, the PCM is placed between the Containment Liner Plate (CLP) and the concrete part of containment building (Fig.1).

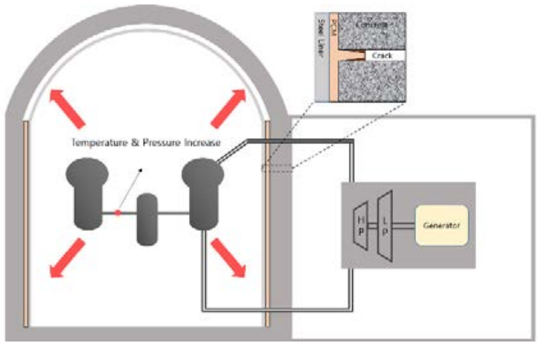

Fig.1. Simple drawing of the nuclear power plant where self-sealing PCM is placed

When an accident occurs, both temperature and pressure usually rise in the containment. If the temperature in the containment exceeds the melting point of the PCM, it starts to be melted and permeate into the cracks either by the pressure difference between the inside and the outside of the containment or by thermal expansion of the CLP. The temperature of the permeating PCM will decrease as it is passing through concrete, and PCM will be frozen if its temperature drops beyond its freezing point. Finally, the crack is sealed by the PCM.

If an accident occurs in the nuclear power plant with unrepaired cracks on the concrete of the containment, there can be a large release of radioactive material to civilian. However, if this concept is applied to the containment building, the cracks can be sealed passively with the PCM, and leakage of a radioactive material can be minimized.

3. Methods

In this section, the shape modeling of the crack and the thermal analysis about the liquid PCM flowing through the crack is introduced. It is recommended to assume the most conservative condition to test the feasibility of new safety technology in the nuclear industry, so that the study can assure the new technology is safe enough to apply in general situation. Therefore, the most conservative condition is assumed in this study.

2.1 Crack Modeling

The shapes of a crack are usually not consistent, so dealing with every type of shape is impossible. In this study, the shape of the crack is assumed to be the straight cylindrical as a representative (Fig. 2). The reason why the straight cylindrical shape is selected as the shape of the crack is that the straight cylindrical shape will allow the PCM to flow most smoothly than other shapes.

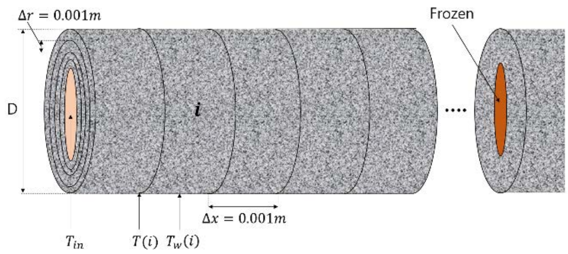

Fig.2. Assumed crack shape with split lines

In other words, it means that the possibility for cracks not to be sealed successfully with the PCM is highest when the shape of the crack is straight cylindrical.

The geometrical values of the cylinder are summarized in Table I. The number of axial nodes is set to 1000, and the number of radial nodes, which are for the concrete part, is set to 10. The size of a crack on concrete usually ranges from hundreds of micrometers to millimeters [2], so the diameter of the cylinder is set to have a value on that range.

Table I. Geometrical variables and corresponding values

Geometrical Variable	Value
Axial Length (L)	$1\ m$
Δx	$0.001\ m$
Δr	$0.001\ m$
Diameter (D)	$0.5, 0.8\ mm$

The analysis was conducted under various sets of the input temperature of the PCM and the pressure inside the containment building. These sets are decided according to some times of SBO accident situation in APR 1400 [3]. Table II. shows the temperature and the pressure used in this study.

For thermodynamic properties, the properties of palmitic acid, one type of an organic PCM, is used. The dynamic viscosity varies as temperature changes, so the dynamic viscosity is changed by the graph fitted with the data in the study of Noureddini et al. [4].

Table II. Set of cases for analysis

Case No.	Inside Pressure (bar)	Input Temperature (°C)
1	3.8	126.7
2	4.7	148.9
3	5.7	154.4
4	6.7	162.8

2.2 Thermal Analysis Method

The thermal analysis code is written in MATLAB to investigate whether PCM can be frozen or not while it flows through the crack.

Firstly, the velocity is traced every time when the PCM passes each node. This is done by finding the velocity that makes the pressure drop equal to the pressure difference between the inside and the outside of the containment building:

$$\Delta p = \left(f(i,j)\frac{\Delta x \cdot j}{D} + K_{inlet}\right)\left(\frac{\rho v(j)^2}{2}\right) \quad (1)$$

The index i expresses the space node, and the index j expresses the time step. For the friction factor, Cheng's empirical correlation that can be applied in both the laminar and the turbulent flow regime is utilized [5]. At the same time, the physical time required to pass one node is also calculated:

$$\Delta t(j) = \frac{\Delta x}{v(j)} \quad (2)$$

Next, Convective heat transfer coefficient is calculated. In the laminar flow regime, Nusselt number is fixed to 3.66, and in the turbulent flow regime, it is calculated using Gnielinski correlation [6].

Finally, the finite difference method (FDM) is used to investigate whether the front of the PCM is frozen or not. The energy balance method is applied between the PCM and the concrete wall (Fig.3). When the temperature of the PCM is higher than its melting point, the heat is transferred from PCM to the wall by both convection and conduction, and the temperature of the PCM decreases during this process:

$$\rho c_p A \Delta x \frac{\left(T(i+1,j+1) - T(i,j)\right)}{\Delta t(j)} = \left(h(i,j) + \frac{2k}{D}\right) A_s\left(T_w(i,1) - T_m(i)\right) \quad (3)$$

Iteration process continues until $T(i+1,j+1)$ converges. This process is repeated to calculate the temperature at every node of PCM ($1 \le i \le j$). The wall temperatures are updated with the FDM at every time step, from the left to the right direction and from the inner to the outer direction.

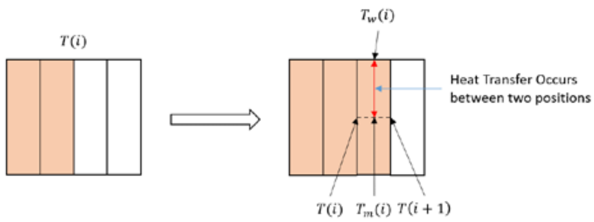

Fig.3. Heat transfer mechanism between PCM and the concrete wall

When the temperature of the PCM reaches its melting point, the heat is still transferred from PCM to the wall by both convection and conduction, and this process makes the phase of the PCM change from a liquid to a solid:

$$\left(\eta(j+1) - \eta(j)\right) h_{PC} \rho A \frac{\Delta x}{\Delta t(j)} = \left(h(i,j) + \frac{2k}{D}\right) A_s\left(T(i,j) - T_w(i,j)\right) \quad (4)$$

The wall temperature and the PCM temperature are updated similarly at every time step, except the nodes where the temperature reached the melting point already. η presents the solid mass fraction of the PCM. η is only investigated at the front node because if the front node is frozen, it means the crack is sealed, and there will be no more flow through the crack. If η becomes larger than one, all processes are stopped, and the node where the PCM is frozen is shown.

4. Results

Fig.4 and 5 show how temperature changes as PCM flows through the crack with each size of the crack. When the diameter of the crack is 0.5mm, the PCM is frozen in every case at a distance less than 0.6m. When the diameter of the crack is 0.8mm, the PCM is also frozen in every case, but the positions where the PCM is frozen are moved toward the outside. In case 4, the PCM is frozen almost at the exit.

The crack shape assumed in this study is the most conservative one. Considering that real cracks on concrete shows more complicated shape and a series of zigzag, the PCM flowing through the real cracks will experience larger pressure drop and finally will achieve lower velocity. The lower velocity will lead PCM to be frozen in most of the cases. Therefore, if this self-sealing concept based on the PCM is applied to the real nuclear containment building, PCM can successfully seal cracks at the accident situation and minimize the leakage of radioactive materials.

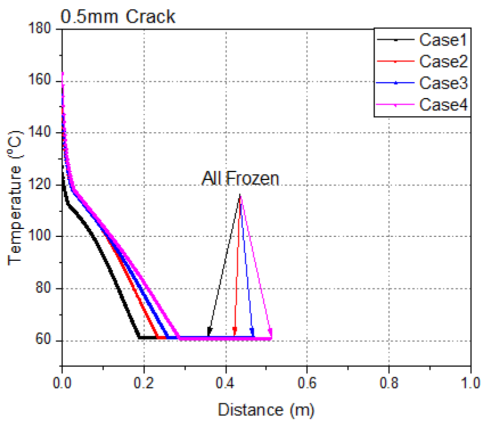

Fig.4. Temperature trend by distance with 0.5mm crack

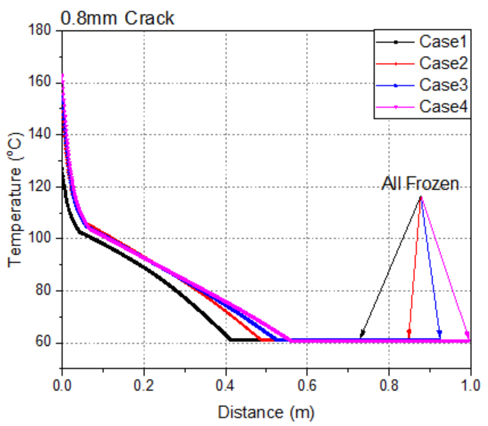

Fig.5. Temperature trend by distance with 0.8mm crack

5. Conclusions

The self-sealing concept based on the PCM is suggested as a passive measure for repairing cracks on the concrete of the nuclear containment building. The feasibility of the concept is investigated with the simulation study about the PCM flow through the crack. In every case, the PCM is frozen successfully, but in some cases at 0.8mm crack, there is too small margin to assure that the PCM can seal the cracks in every situation. However, considering that this study assumed the most conservative crack shape for simulation, the PCM can successfully seal the cracks in general situation, which shows a complicated crack shape. Therefore, if this self-sealing concept is applied, it is expected to efficiently enhance the leakage sealing capability of the containment building. For further work, the more complicated crack shape will be modeled and analyzed by the same code, and the code verification will be conducted with some experiments.

ACKNOWLEDGMENT

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NOMENCLATURE

A	$[m^2]$	Flow area
A_s	$[m^2]$	Surface area that contacts with the wall
c_p	$\left[\frac{J}{kg\cdot K}\right]$	Specific heat
D	$[m]$	Crack Diameter
f	$[-]$	Friction factor
h	$\left[\frac{W}{m^2\cdot K}\right]$	Convectional heat transfer coefficient
h_{PC}	$\left[\frac{J}{kg}\right]$	Latent heat
i	$[-]$	Space node
j	$[-]$	Time step
K_{inlet}	$[-]$	Inlet form loss coefficient
k	$\left[\frac{W}{m\cdot K}\right]$	Thermal conductivity
L	$[m]$	Crack Length
T_m	$[°C]$	Temperature at the middle between two nodes
T_w	$[°C]$	Wall temperature
Δt	$[s]$	Physical time required to pass node
Δr	$[m]$	Radial spacing
v	$\left[\frac{m}{s}\right]$	Velocity
Δx	$[m]$	Axial spacing

Greek Symbols

η	$[-]$	Solid mass fraction
ρ	$\left[\frac{kg}{m^3}\right]$	Density

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