CFD Analysis of Heat Removal Capability in a Natural Circulation Loop with Phase Change Material

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1. Introduction

Over last a few decades passive cooling technology using phase change materials (PCM) associated with thermal energy storage (TES) principle has been investigated as an energy beneficial technology in terms of low-carbon emission along with economic efficiency. Since PCM absorb and discharge heat through solid-liquid phase change process when temperature fluctuates, considerable attention has been paid to passive cooling and heating technology utilizing PCM. Accordingly, many efforts have been put into researching for its application to diverse areas. This technology has been utilized variously from cooling space craft control to cooling electronics [1,2].

As mentioned earlier, one of the applications is cooling indoor buildings when the buildings encounter overheating problems by internal heat loads. In general, two approaches are available in order to incorporate PCM to building cooling applications. Active approach requires any mechanical equipment or devices such as fans or HVAC systems to control the PCM thermal energy. In passive way PCM thermal energy is either released or charged depending on only natural convection heat transfer on the system boundary. Therefore, in the case of extreme event such as neither electrical nor battery power available, passive approach is the only way to remove the heat loads generated inside building.

Various PCM are utilized according to applications. PCM is classified largely as three groups based on chemical compounds: organic, inorganic, and eutectic mixtures [3]. Inorganic and organic groups are mainly utilized for heating and cooling buildings [4]. Inorganic PCM, such as salt hydrates and metals, has excellent properties in terms of latent heat capacity as well as thermal conductivity. In the meantime, both materials have disadvantages such as corrosiveness and instability. When PCM is incorporated into the passive system, its thermal performance on inside buildings is affected by not only its material characteristic but also its geometrical shape of installed cooling system. Therefore, it may be required that the thermal performance of passive system needs to be numerically analyzed since the passive system accompanies complex heat transfer phenomena. Numerous articles related to PCM thermal applications have been published over the last decades. In this paper, a simulation on natural circulation loop with encapsulated PCM, which is composed of PCM and air, is presented.

2. Simulation Methodology

The passive system used in the simulation is filled with water, receives heat from the heat source, circulates through natural convection, and transmits heat to the heat sink.

In the simulation, the heat removal capability was calculated by comparing the total amount of heat coming from the heat source with the amount of heat removed from the heat sink. To implement this simulation, k- epsilon turbulence model was used with DEM (Discrete Element model) in Lagrangian multiphase, segregated flow, two layer all y+ wall treatment, etc. Fig. 1 and Fig. 2 show the passive cooling system dimensions and boundaries, respectively. Surfaces highlighted as red are heat sources and the heat sinks are highlighted as blue.

All boundaries except Heat source and Heat sink are adiabatic. The top and bottom flow channels of the passive device were designed as converge-diverge shape in order to facilitate flow of PCM capsules.

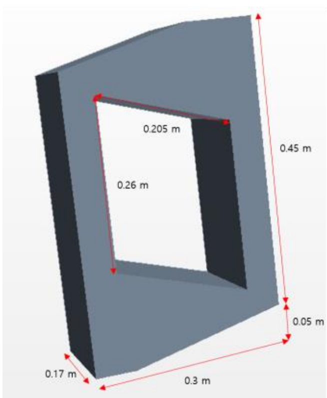

Fig. 1. Dimensions of the passive system

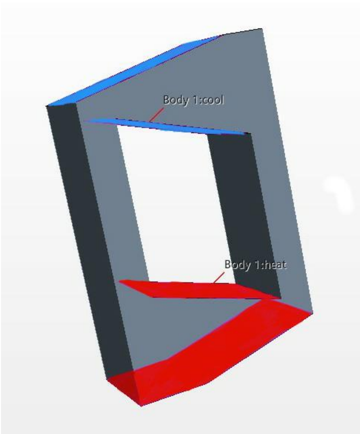

Fig. 2. Boundaries (heat source and heat sink)

Two cases are simulated in order to investigate the effect of the PCM. The first case is implemented with filling the device with water only. Another case is performed with filling the device water and PCM capsules.

Fig. 3 presents the initial conditions of temperature and pressure. The overall distribution of the initial conditions is graphically visualized in Fig. 3. Table I presents the boundary condition of the passive system.

Table I: Boundary conditions

Heat source: constant temp	340 K
Heat sink: constant temp	280 K

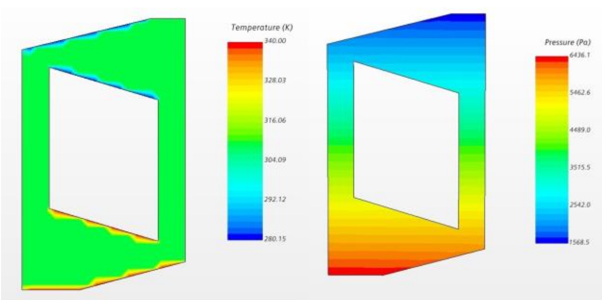

Fig. 3. Initial temperature & pressure

In this simulation, encapsulated PCM was put into water to accelerate natural convection and to see how heat removal performance changes. In order to utilize PCM capsules into the simulation, the properties of the PCM, such as density and specific heat, were incorporated into the simulation system as user-defined field functions. The properties of the PCM used in the simulation are artificial, but these values are referenced to a value similar to that of the inorganic PCM [5].

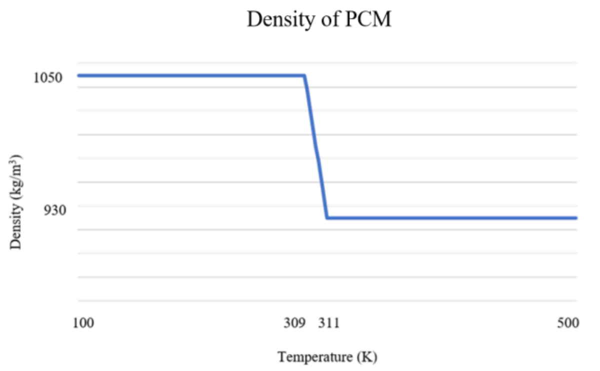

Fig. 4. Density of PCM

As shown in Fig. 4, the density is set to vary linearly between 309 K and 311 K. Between 100 K and 310 K, the density maintains 1050 kg/m^3 in solid state and between 311 K and 500 K, the density maintains 930 kg/m^3 in liquid state. In order for the natural circulation of water to be accelerated by buoyancy and drag force of the PCM, the density must be greater than that of water when the PCM is solid and less dense than water when it is liquid. This can be satisfied by injecting an adequate amount of air into the PCM capsule.

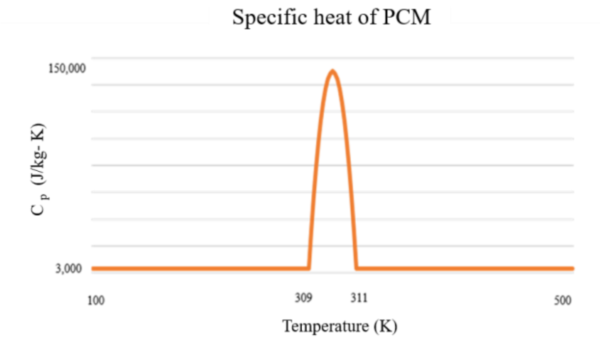

Fig. 5. Specific heat of PCM

The specific heat is 3,000 J/kg in both liquid and solid regions as presented in Fig. 5. However, in the region where solid-liquid phase change takes place, the following polynomial function was utilized.

$$C_p(T) = -147000T^2 + 9.114\times10^7\,T - 1.412655\times10^{10} \quad (1)$$
$$(309\text{ K} < T < 311\text{ K})$$

This polynomial function was designed to produce the latent heat by integrating the mushy zone. The use of this strategy is due to the nature of the DEM model used to track solid particle behaviors of the PCM in this numerical simulation. Since phase change is restricted in the DEM model, phase change (solid - liquid) needs to be expressed artificially using the polynomial function with respect to C_p described above.

The overall specifications of the PCM capsule assumed in the numerical simulation are summarized in the table II.

Table II: PCM property

Particle diameter	0.01 m
Initial particle temp.	300 K
Melting temp.	310 K
Latent heat	202,000 J/ kg
Specific heat	3000 J/kg·K
Number of PCM	503
Total mass of PCM capsules	0.2765 kg
Mass fraction of PCM capsules	1.35 %
PCM Capsule Density	1050 kg/m^3 (Solid state) 930 kg/m^3 (Liquid state)

3. Results and Discussion

The thermal-hydraulic output values for two cases are presented in Table III below. All the numbers were averaged based on the values after achieving quasi-steady state. According to the results, it is clear that when PCM is utilized in the passive system, about 5 times more heat is absorbed and discharged to the ambient compared to the case of water only. Also, the temperature of the second case (water + PCM) is 4 K lower than the case without PCM capsules.

Table III: Summary of analysis results

Output	Water	Water + PCM
Mean temperature	314.60 K	310.58 K
Q_{in}	1140.1 W	5280.09 W
Q_{out}	-1137. 549 W	-5226.566 W
$\Delta Q/Q_{in}$	0.224 %	1.01 %
Mass flow rate	0.1578 kg/s	0.2404 kg/s
Water velocity	0.01875 m/s	0.02844 m/s

Outputs are described as the followings:

Q_{in}: Total amount of heat from heat source
Q_{out}: Total amount of heat removed by heat sink
ΔQ: Sum of Q_{in} and Q_{out}

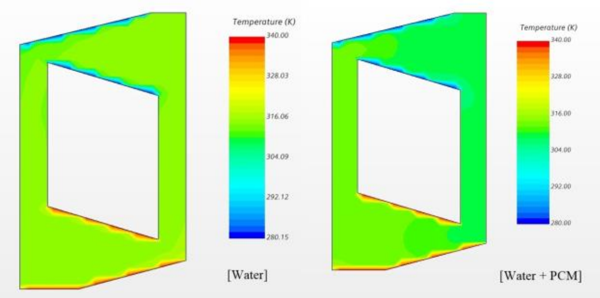

Fig. 6. Temperature distribution

The effect of heat transfer enhancement using PCM is observed in Fig. 6. As described in Table III, the graphic results indicate the second case (water & PCM) temperature is slightly lower than that of the first case (water). These results are due to PCM's relatively large latent heat and good circulation in the device.

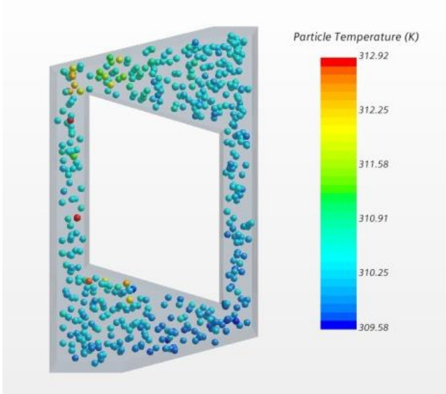

Fig. 7. Particle temperature

The temperature of flowing PCM capsules is presented in Fig. 7. It is clearly shown that PCM capsules smoothly flow through the channels by buoyancy effect caused by solid to liquid phase change process. Also, the PCM capsules' movements by buoyancy force provide momentum with the water so that the water flows upward faster. The disparity of the water velocity indicated in Table III is explained as above. Fig. 8 depicts that the pink flat rectangle points out where the mass flow rate and water velocity were evaluated. The arrows in Fig. 8 indicate the instantaneous velocity of the PCM particles, and the color and size of the arrow express the velocity magnitude.

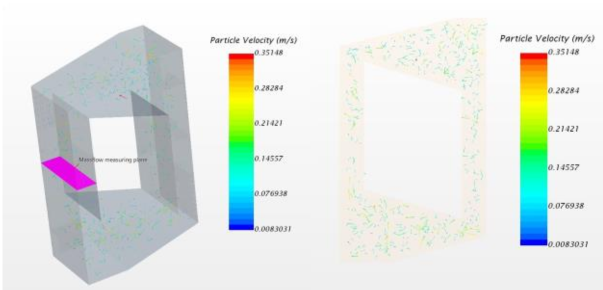

Fig. 8. Particle velocity

4. Conclusion

The results obtained in the present study show that about 5 times more heat is absorbed and discharged to the ambient due to the effect of unique feature of PCM compared to the case of water only. This results suggest that PCM is highly effective in passive systems with no active devices. In other words, the presented passive system may have potential advantages for cooling a vital area such as main control room (MCR) during total loss of power accident in a nuclear power plant. Though the PCM properties used in the current numerical analysis are artificial, they are determined based on realistic values. PCM properties are also adjustable by mixing different PCM with current technology level if necessary.

It is clearly shown through CFD analysis that heat removal performance is noticeable when passive cooling is achieved through natural convection using PCM. Particularly, the case with 1.35% mass fraction of PCM shows significant effect of PCM capsule usage. If mass fraction of PCM is increased, the heat removal capability of the passive system is expected to be improved. In the near future, sensitivity studies will be continued for different equipment geometry, working fluid, and the required properties of PCM.

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