Heat Transfer Experiment with PureTemp58X for Passive Containment Cooling Application

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1. Introduction

The role of the Passive Containment Cooling Systems (PCCSs) has become more significant since the Fukushima Daiichi nuclear power plant accident. The Westinghouse Corporation was first in applying the PCCS to a commercial nuclear power plant, AP1000 [1]. In Korea, several different PCCS concepts have been developed. They are heat exchanger modules and thermosyphon assembly [2, 3]. Theses PCCSs were designed to be installed inside the containment and transfer the released heat to the water pool outside the containment. However, the PCCS of AP1000 cannot be applied to the Korean operating PWRs directly. On the other hand, several limitations exist for the heat exchanger modules and thermosyphon assembly. Since they can only be installed in newly constructed nuclear power plants, it is not suitable for application in operating nuclear power plants. Also, both PCCS concepts were designed to penetrate the containment wall to connect the heat exchangers to the outside water pool. The penetration adds the risk of radioactive material release by introducing another potential pathway.

In order to simplify the PCCS design and eliminate the risk of radioactive material release, the KAIST research team proposed a new PCCS concept, a condenser using a phase change material (PCM) as shown in Fig. 1. The PCM acts as the final heat sink and absorbs the heat. The heat is transferred through the copper thermal conductor. As a simple system, this condenser does not need to penetrate the containment wall for installation. Thus, it has the potential applicability for operating PWRs and can work with other PCCSs to improve the cooling efficiency. The main target nuclear reactor is the APR1400 but it also can be applicable to many other designs.

To apply the PCM heat sink to a commercial reactor, it is crucial to understand how much and how fast heat can be removed from the system. However, most of the PCM candidates have very low thermal conductivity. To efficiently remove heat, heat fin structure is essential. This study aims to see the heat transfer performance of a certain PCM with a given heat transfer structure.

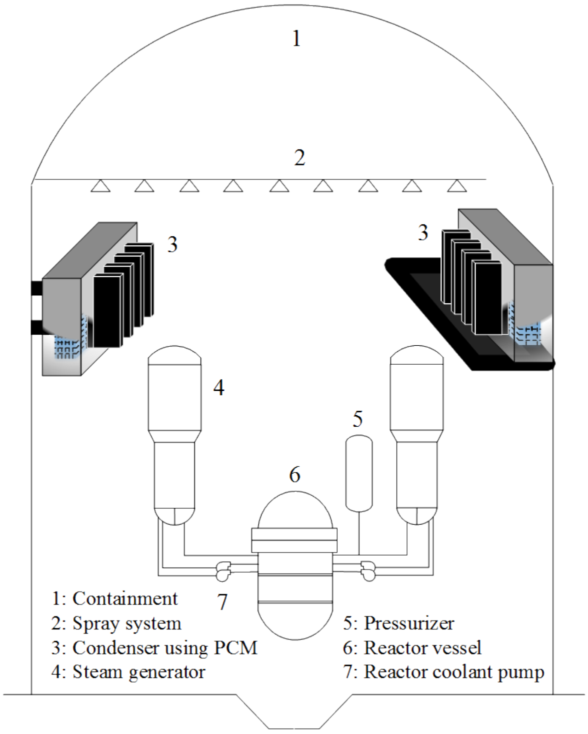

Fig. 1. Schematic diagram of the PCCS and Primary cooling system within the containment

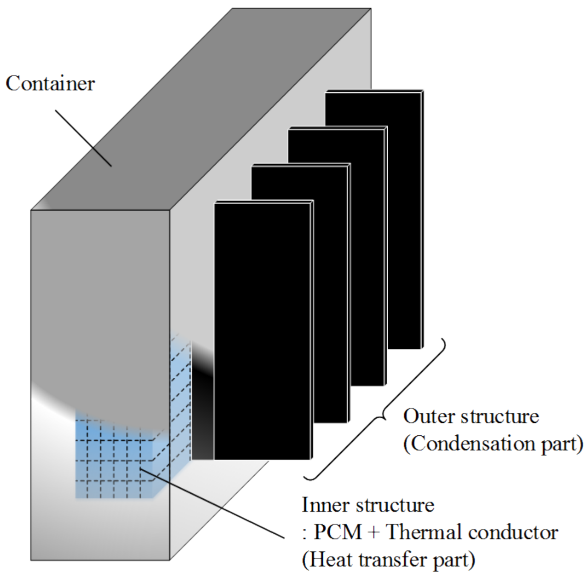

Fig. 2. Conceptual Design of PCM steam condenser module

2. Experiment Setup

Several candidate PCMs were selected for PCCS in previous works [4]. PCM product named PureTemp58X was selected for this case. As can be inferred from the name, the material melts at 58 degrees Celsius. Thus, it will stay solid in normal operation of NPP and only go through phase change in accident situations.

Steam Temperature was set to 150 degrees Celsius and pressure was maintained at saturation pressure, which is around 4.7MPa.

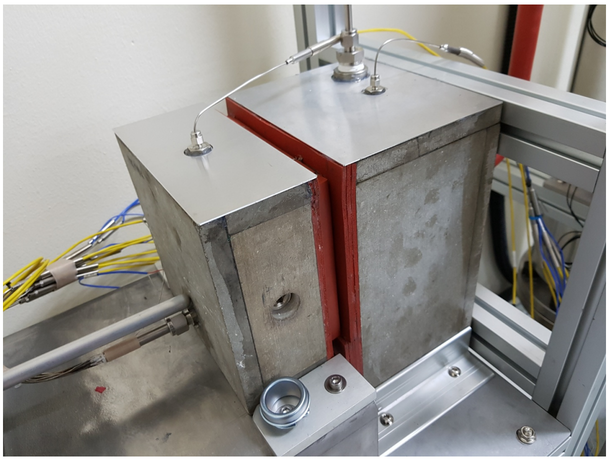

Fig. 3. Heat Exchanger with PCM chamber on the left and steam chamber on the right

3. Results

It took nearly 1000 seconds for the whole PCM volume to change from solid to liquid phase. Temperature profiles of different measure points are shown in Fig. 4. The blue dotted line shows the melting point of the PCM used.

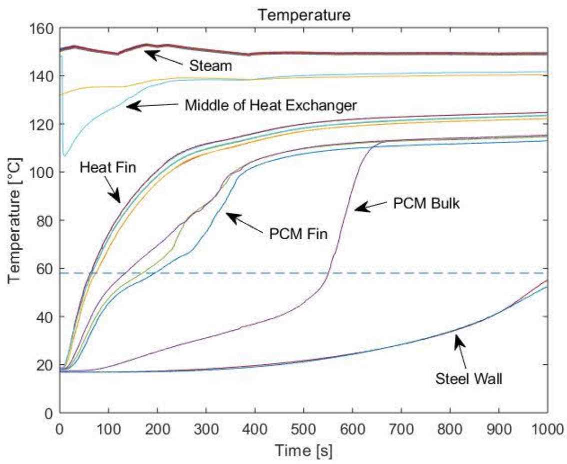

Fig. 4 Temperature Profile at different measure points

Temperature of copper heat fins increased steeply while the temperature of PCM increased slowly. Temperature of PCM near the copper fins reached melting point in around 150s while the temperature in the middle of the PCM bulk took around 550s to reach the melting point. It shows that the performance of the PCM system deeply relies on the configuration of the heat fins as temperature rise is highly dependent on the distance to the copper fins. The melting point provided by the vendor is 58 degrees Celsius. However, it is difficult to see a temperature plateau near the melting point. This is probably because the product is a mixture of different compounds. However, the vendor does not disclose the chemical composition of its products.

We can calculate the amount of heat absorbed by the PCM using the temperature from different measure points. Thermocouples were placed between the fins to see the temperature behavior of PCM near fins. Another thermocouple was placed in the bulk of the PCM further from the heat source. Nearly half of the PCM was within 10mm from the fin. The mean temperature from three thermocouples placed between the fins was used to calculate the heat absorbed by the PCM near the fins. The temperature from the thermocouple in the bulk of the PCM was used for the rest of the PCM.

The sum of the PCM bulk and PCM near fins is shown in the figure below. The sum of the heat absorbed increases in two steps. This is because we are using two representative temperature values to calculate. The actual heat absorbed by the PCM will actually increase steadily until it reaches a saturation point around 650s.

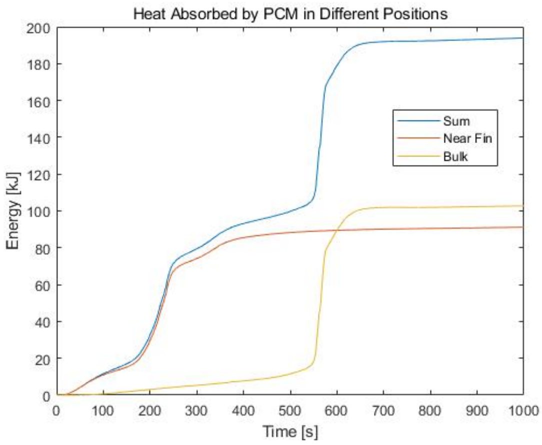

Fig. 5 Heat absorbed by PCM

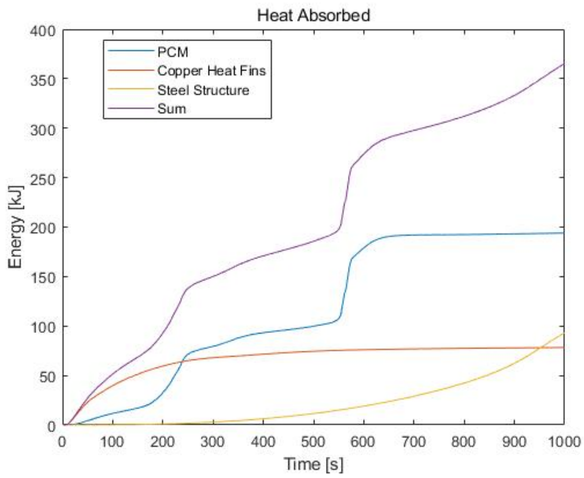

Fig. 6 Heat Absorbed by different parts of the module

The amount of heat absorbed by different parts of the heat transfer module is shown in Fig. 6. By the end of the experiment, 357kJ of heat was absorbed in the PCM, copper fins, and steel walls. Half of the heat absorbed was in the copper heat fins and steel walls. The Copper temperature rises rapidly in the beginning due to its high thermal conductivity. With several PCM condenser modules, the amount of copper will be substantial. Although the main role of the copper is to effectively transfer the heat to the PCM, it can also help absorb heat in the initial phase of an accident when high temperature steam rapidly ejects from the main system into the containment volume due to the huge pressure difference. As copper temperature increases, the amount of heat absorbed by the PCM also starts to increase. After all the PCM has melted, the steel structure starts to absorb the heat.

4. System Design

The effective thermal conductivity and heat transfer area needed for the PCM condenser to satisfy the requirement performance for PCCS were calculated. From the CAP code analysis of the team [4], it was identified the product of heat transfer area and effective thermal conductivity must be above 180 kW˙m/K as shown in Fig. 7.

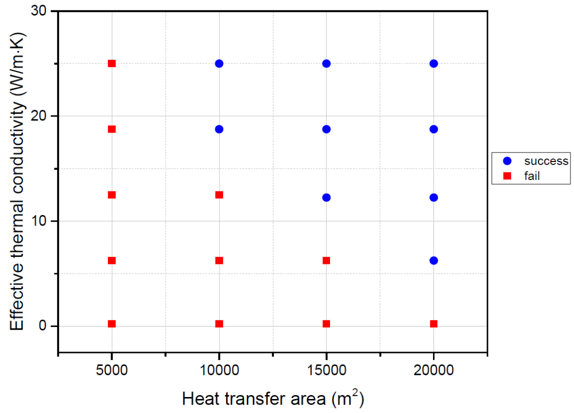

Fig. 7 Requirements for P58X PCM condenser for PCCS criteria

Using the equations below, we can calculate the effective thermal conductivity measured from the experiment.

$$\dot{Q} = \frac{k}{L} A\left(T_s - T_{PCM,t}\right) = \frac{mC_p\left(T_{PCM,t} - T_i\right)}{t} \quad (1)$$

$$kA = \frac{mC_p L\left(T_{PCM,t} - T_i\right)}{t\left(T_s - T_{PCM,t}\right)} \quad (2)$$

$\dot{Q}$: Power
k: effective thermal conductivity of the PCCS
L: thickness of PCM
A: total heat transfer area of the PCCS (copper plate outer side)
T_s: steam temperature
$T_{PCM,t}$: PCM temperature at time t
m: total mass of PCM
C_p: specific heat of PCM
T_i: initial temperature of PCM
t: time

The effective thermal conductivity measured from the experiment can be plotted as below. The conductivity spikes when temperature reaches melting point but saturates to around 10W/m˙K. To see if our PCM condenser module satisfies the requirements, the product of thermal conductivity and heat transfer area was calculated. The graph below shows that the value of the product saturates to around 5000 kW·m/K. The value is much higher than the requirement, which is 180 kW·m/K. Therefore, if the cooling module is designed to maintain its heat transfer performance for 72 hours, the module can be used as a PCCS.

In our experiments, the PCM was separated from the steam with two copper plates with thermal grease applied on the interface. Although the grease helped decrease the thermal resistance, we can actually achieve higher performance in the actual case where a single copper plate is exposed to steam directly. Therefore, the actual effective thermal conductivity will be even higher in the actual case.

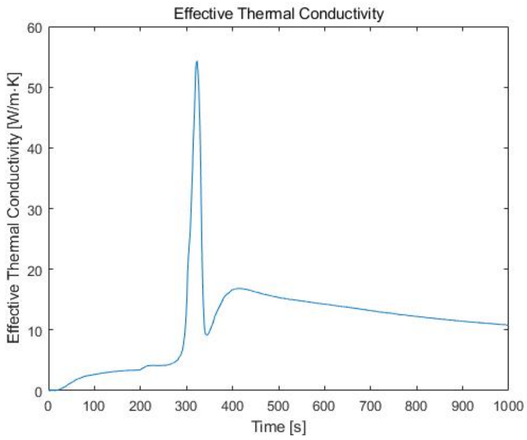

Fig. 8 Effective Thermal Conductivity

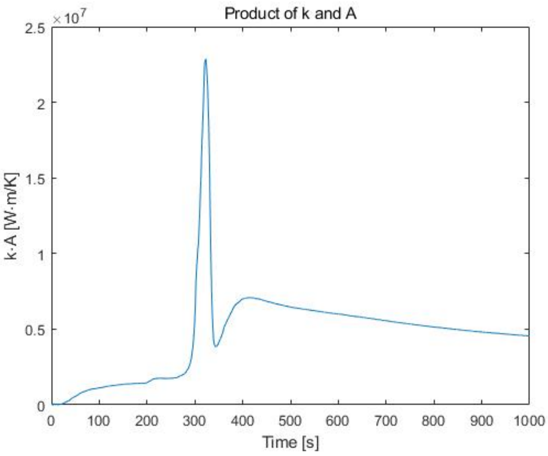

Fig. 9 Product of Thermal Conductivity and Area

5. Conclusions

PCCS using PCM can be applied to existing nuclear power plants without containment penetration. PCM condenser experiments were conducted to check the actual heat absorption performance of the PCM condenser. The results were promising and it matched the criteria suggested by our previous works. Therefore, the PCM condenser is a promising technology for application in the current and future nuclear power plant safety.

ACKNOWLEDGEMENTS

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