Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

Parametric Study for Designing PCM Condenser as PCCS for APR1400

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1. Introduction

The role of the Passive Containment Cooling Systems (PCCSs) to ensure the safety and integrity of the containment has become more important since the Fukushima Daiichi nuclear power plant accident. Several concepts of PCCSs exist but each concept was designed to be applicable to a specific type of nuclear reactor. In Korea, heat exchanger modules and the thermosyphon assembly were developed for the PCCS of APR1400 [1, 2]. These PCCSs were designed to be installed inside the containment and transfer the released heat to the water pool outside the containment. It means that the containment wall should be penetrated and the additional facilities are necessary to connect them.

In order to simplify the PCCS design and eliminate the risk of release of the radioactive material, the KAIST research team proposed the new PCCS concept, the condenser using the phase change material (PCM) as shown in Figs. 1 and 2. As a simple system, this condenser has the potential applicability for even operating PWRs and can work with other PCCSs to improve the cooling efficiency. The main target nuclear reactor is APR1400.

To specify the PCM condenser design, various design parameters, which can affect its performance, should be evaluated. Thus, as the first step of parametric study, a parametric calculation for the effect of finger number was carried out to confirm the heat removal capability of PCM condenser using the commercial unstructured finite volume code (STAR-CCM+ v.11.06.010). Then, the result was compared to that of the performance of heat exchanger module type PCCS conducted by Bae et al. (2015) [1].

2. Methods and Results

2.1 Simulation Domain

This study focused on the assessment of heat transfer performance of PCM condenser, so the number of copper finger as the thermal conductor that transfers heat to PCM was the main parameter. Since there is no pre-determined parameter, the dimensions of the condenser unit were arbitrary selected as shown in Fig. 3. The copper fingers (the number of fingers: 1~6) with regular intervals are attached on the copper plate and contact with PCM.

The computational grid generation was performed based on the trimmed shape mesh with various element sizes. Local temperature profiles were selected to obtain the grid convergence index (GCI), which represents the discretization errors in series of grid resolutions. In this study, the base size was set to 1% of the y-directional domain satisfying the recommended GCI values [3, 4].

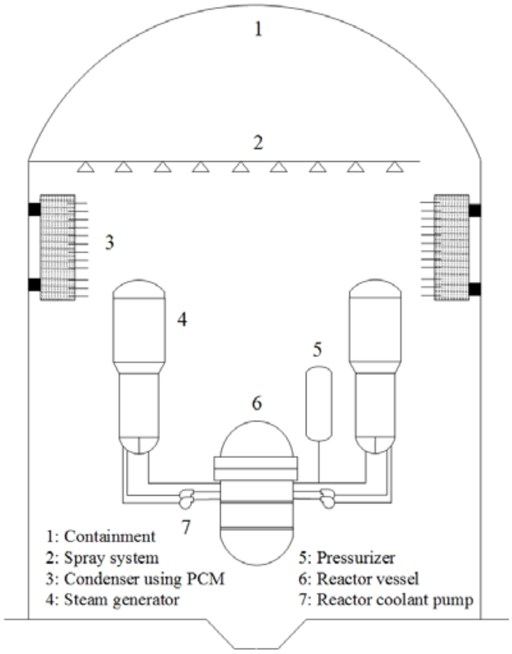

Fig. 1. Configuration of PCM condenser in the containment

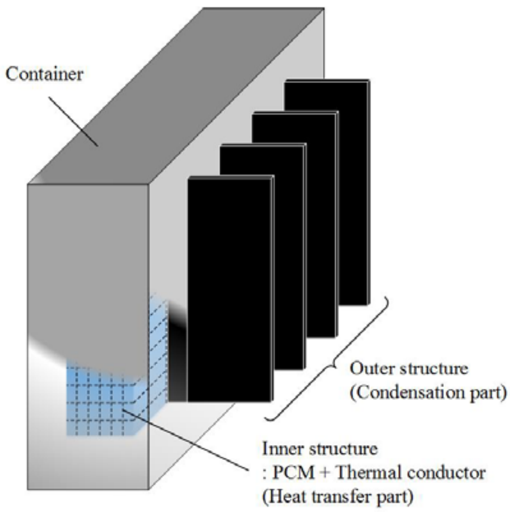

Fig. 2. Structure of the PCM condenser

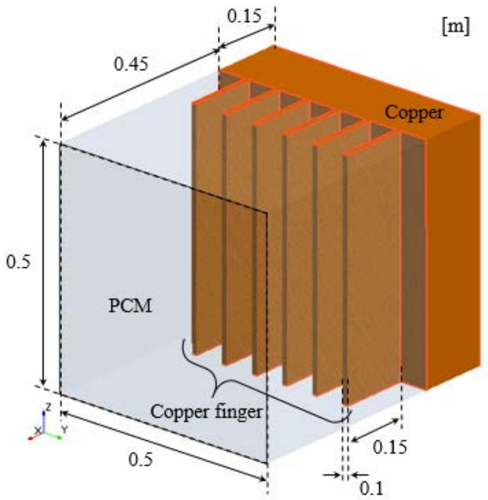

Fig. 3. Schematic diagram of simulation domain with 6 copper fingers

2.2 Initial and Boundary Conditions

This problem was solved based on the heat transfer as conduction through the copper plate, finger and PCM. The initial temperature through whole structures was set as 25°C. As the boundary conditions, the constant temperature by 100°C was given on the opposite surface of copper plate that fingers are attached and the outer surfaces were set to be adiabatic. The contact resistance of the interface between the copper fingers and PCM was neglected because there is no information. This factor will be found by conducting the experiment later.

Climsel C70 was chosen as the PCM used in this simulation from the results of the screening process. To simulate the phase change of Climsel C70, the effective heat capacity method was used because the PCM melts over a temperature range. The effective heat capacity for each phase change period is given as follows [5]:

$$c_{eff} = \begin{cases} c_s & T < T_1 \quad \text{solid} \\ L/(T_2 - T_1) + c_s & T_1 \le T \le T_2 \quad \text{mushy} \\ c_l & T > T_2 \quad \text{liquid} \end{cases} \quad (1)$$

Table I: Properties of Climsel C70 [6] and copper

	Climsel C70	Copper
Melting temperature range (°C)	70~76	-
Density (kg/m^3)	1400 (solid, liquid)	8940
Latent heat of fusion (J/kg)	144000	-
Specific heat (J/kg-K)	3600 (solid, liquid)	386
Thermal conductivity (W/m-K)	0.81 (solid, liquid)	398

where, c_s and c_l is specific heat of solid and liquid PCM in J/(kg·K), respectively. The material properties of the used PCM and copper are listed in Table I. The properties of the PCM in the liquid state were not available so it was assumed that the properties of liquid state are the same as those of solid state.

2.3 Results and Discussion

Figs. 4 and 5 show the results of the heat transfer rate through the copper and PCM, respectively. It seems like that the number of fingers has no noticeable effect on the heat transfer through the copper. On the other hand, as the finger number increases, the heat transfer through the PCM increases. This can be also confirmed from the results of the total heat removed for 20,000 seconds as shown in Fig. 6.

The main function of copper is to improve the heat transfer to the PCM by designing the copper structure due to the low thermal conductivity of PCM. Thus, it can be said that the heat removal capability of the PCM condenser is determined by the heat that the PCM part absorbs.

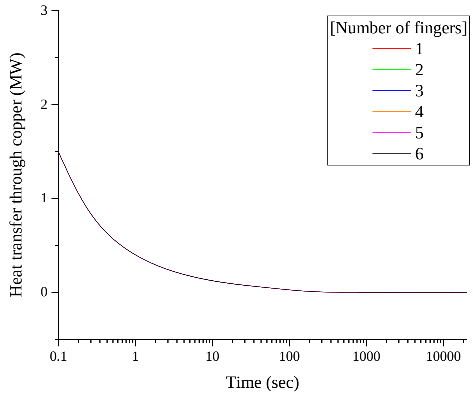

Fig. 4. Heat transfer through copper

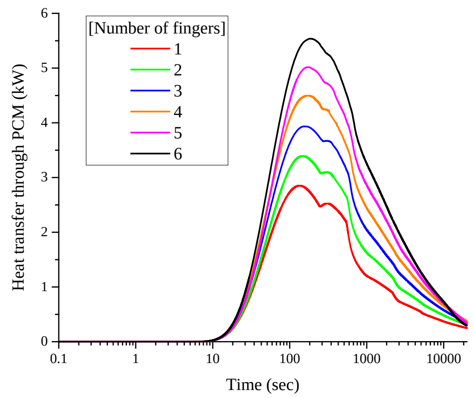

Fig. 5. Heat transfer through PCM

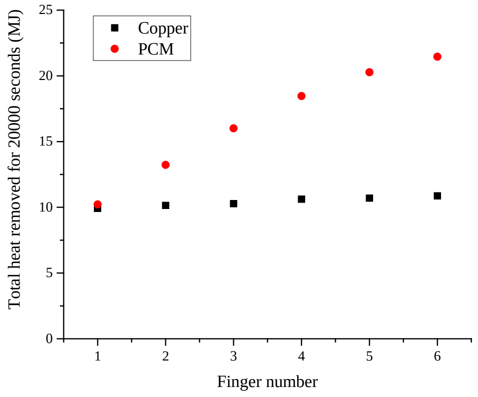

Fig. 6. Total heat removed for 20,000 seconds varying with the copper finger number

The total heat removal capacity of the heat exchanger module type PCCS is about 487,085 MJ during 20000 seconds with the total heat transfer area ─ the area of the surface that meets the atmosphere of containment ─ of 6,776 m^2 [1]. In the case of the PCM condenser of this study, the total heat removal capacity is equivalent to that of heat exchanger module type when there are 22,707 PCM condenser units with the total heat transfer area ─ the area of the surface without finger in this condenser ─ of 5,677 m^2. The PCM condenser needs smaller heat transfer area than the heat exchanger module type. It means that to design the PCM condenser makes a positive result to cool down the containment.

3. Summary and Further Works

As new PCCS concept, the condenser using the phase change material was proposed and a parametric study was performed to design it. It was confirmed that the more fingers, the more heat is transferred to and absorbed in the PCM. Also, the PCM condenser showed the possibility to achieve the target heat removal capacity as the PCCS.

As the next step, to determine the specific design, more parameters such as the thickness of copper plate and finger or the length of finger will be studied to improve the effective thermal conductivity of the structure. The part that the condensation occurs will be also designed and evaluated.

ACKNOWLEDGEMENT

This research was supported by the KUSTAR-KAIST Institute, KAIST, Korea.

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