Conceptual Design of Condenser using PCM as PCCS for APR1400

Hwa-Young Jung [a], A-Reum Ko [a], Jeong Ik Lee [a*], Ho Joon Yoon [b]
[a] *Dept. Nuclear & Quantum Eng., KAIST, 291, Daehak-ro, Yuseong-gu, Daejeon, 34141, Republic of Korea*
[b] *Dept. Nuclear Eng., KUSTAR, Al Zafranah, Abu Dhabi, United Arab Emirates*
[*] *Corresponding author: jeongiklee @kaist.ac.kr*

1. Introduction

After the Fukushima Daiichi nuclear power plant accident, the importance of the Passive Containment Cooling Systems (PCCSs) for removing the heat released to the containment gained more interest than before. The Westinghouse Corporation firstly applied the PCCS to the commercial nuclear power plant, AP600, then, AP1000 [1]. On the other hand, in Korea, several different PCCS concepts from those of AP600 have been studied. These concepts include installing heat exchangers or a Multi-Pod Heat Pipe (MPHP) assembly and transferring the released heat to the water pool outside the containment [2, 3].

In this study, the conceptual design of the condenser using the phase change material (PCM) is proposed as another PCCS concept for PWRs. Only this condenser will be installed inside the containment as shown in Fig. 1, so it is not necessary to penetrate the containment wall to connect the additional facilities outside the containment with inner heat exchangers using pipes. Thus, it is possible to install the condenser for the existing nuclear power plants under operation without PCCS. Most of all, this condenser has to be designed to reduce the pressure and temperature in the containment until the containment spray system is available. A feature of the condenser as shown in Fig. 2 is the composition of PCM and wire mesh connected with the fins to improve heat transfer. As the first step, a preliminary study was conducted to find the optimum design of the part at which the condensation occurs under the given conditions.

2. Methods and Results

2.1 Condensation Model

In this model, the Advanced Power Reactor 1400 (APR1400) was selected as a reference reactor. The type of fin was determined as a vertical flat plate and the array of fins is in single row to avoid the effect of condensate falling from the upper fin and placed at regular intervals on the fin base.

To simplify the model, it was assumed that the containment is filled with the saturated steam without noncondensable gases. The film of condensate on the fin surface was considered as laminar film in all regions (i.e. the wave-free laminar ($Re_L \leq 30$), wavy flow ($30 < Re_L \leq 1800$), and turbulent ($Re_L \geq 1800$) region. The

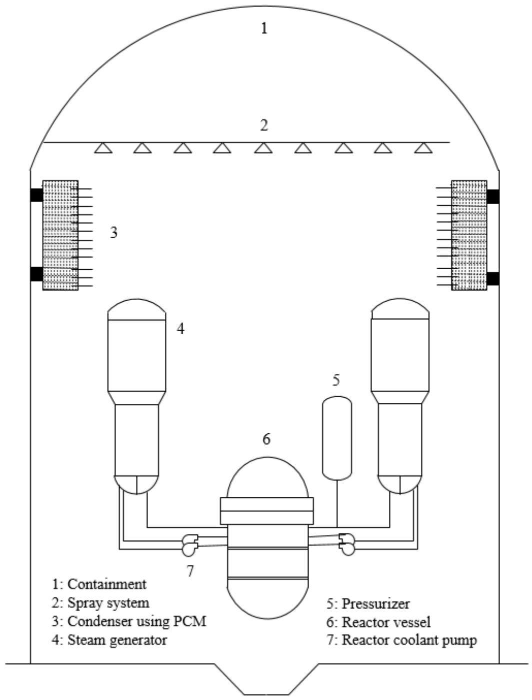

Fig. 1. Configuration of condenser using PCM in the containment

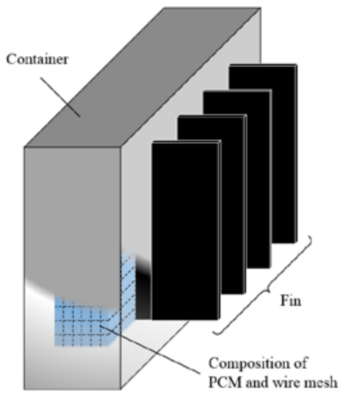

Fig. 2. Structure of condenser using PCM

heat transfer effects of fin thickness and fin base were neglected.

The initial containment atmospheric conditions were set as the maximum pressure of 0.74MPa due to the large break loss-of-coolant accident (LBLOCA) [4] and the corresponding saturated temperature of 167.2°C. The fin temperature was assumed to be isothermal and equal to the PCM temperature connected with the fins without wire mesh. As the PCM, the PureTemp 60 was selected for this preliminary study and its information is summarized in Table I [5]. Based on the initial temperature of containment and fin, the properties of film as saturated water on the fin surface were evaluated at the film temperature, $T_f = (T_{sat} + T_w)/2$.

Table I: Properties of PureTemp 60

Property	
Melting temperature (°C)	61
Density (kg/m^3)	960 (solid)
Latent heat of fusion (kJ/kg)	220
Specific heat (kJ/kg-K)	2.04 (solid)

The following equations [6] were used to calculate the modified heat of vaporization in Eq. (1), the film thickness in Eq. (2), the condensation rate in Eq. (3), the Reynolds number at the bottom of the fin according to the flow region in Eqs. (4)~(6), and the average condensation heat transfer coefficient for the film of length L in Eq. (7),

$$h'_{fg} = h_{fg} + 0.68 c_{p,l} (T_{sat} - T_w) \quad (1)$$

$$\delta(L) = \left[\frac{4 k_l \nu_l (T_{sat} - T_w) L}{h'_{fg}\, g (\rho_l - \rho_\upsilon)} \right]^{1/4} \quad (2)$$

$$\dot{m} = \frac{q}{h'_{fg}} = \frac{\bar{h}_L A (T_{sat} - T_w)}{h'_{fg}} \quad (3)$$

$$\mathrm{Re}_L = 3.78 \left[\frac{k_l L (T_{sat} - T_w)}{\mu_l h'_{fg} \left(\nu_l^2 / g \right)^{1/3}} \right]^{3/4} \quad (\mathrm{Re} \le 30) \quad (4)$$

$$\mathrm{Re}_L = \left[\frac{3.70 k_l L (T_{sat} - T_w)}{\mu_l h'_{fg} \left(\nu_l^2 / g \right)^{1/3}} + 4.8 \right]^{0.82} \quad (5)$$

$$(30 < \mathrm{Re} \le 1800)$$

$$\mathrm{Re}_L = \left[\frac{0.069 k_l L (T_{sat} - T_w)}{\mu_l h'_{fg} \left(\nu_l^2 / g \right)^{1/3}} \mathrm{Pr}_l^{0.5} - 151 \mathrm{Pr}_l^{0.5} + 253 \right]^{4/3} \quad (6)$$

$$(\mathrm{Re} > 1800)$$

$$\bar{h}_L = \frac{\mathrm{Re}_L\, \mu_l h'_{fg}}{4 L (T_{sat} - T_w)} \quad (7)$$

The target design capacity of the proposed condenser was set as 20MW. The width and thickness of fin were fixed and the width and length of fin bas were limited. The length of fin, which is set to be equal to that of fin base, is also limited. The design information is summarized in Table II. The number of fins were calculated by considering the fin spacing, which is equal to twice of the fin thickness since the condensation occurs on both side of a fin. For the predetermined fin length, the film thickness at the bottom of the fin calculated from Eq. (2) was confirmed to not exceed the fin thickness. Dimensions of fin and fin base satisfying the target design capacity of 20MW were obtained.

Table II: Design Parameter of Fin and Fin base

		Dimension (mm)
Fin	Width	300
	Length	100~2000
	Thickness	1
Fin base	Width	100~2000
	Length	100~2000

2.2 Results and Discussion

Fig. 3 shows the results of the total heat transfer area of fins, the average condensation heat transfer coefficient, the fin base area, and the number of fins while varying with the fin length. The results show that the fin base area as well as the total heat transfer area of fins are generally in inversely proportional to the average condensation heat transfer coefficient. Also, the point at which the gradient is changed is when the flow regime is changed from wavy flow to turbulent flow. However, the number of fins shows the different trend. Thus, in order to achieve better average condensation heat transfer coefficient under the identical heat capacity condition, the shorter the fin length and the more fins are necessary for the optimum design the condenser in wavy flow region. In contrast, the opposite satisfies the optimum design for turbulent flow region.

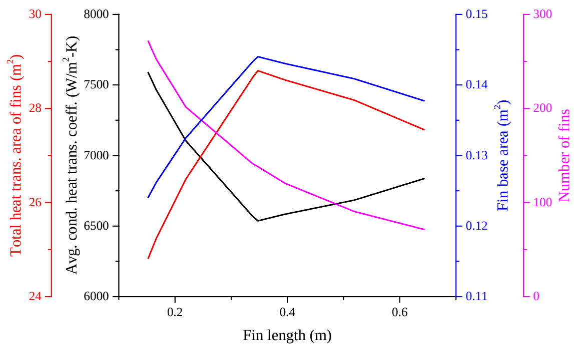

Fig. 3. Results of preliminary study

3. Summary and Further Works

In this study, to find the optimum design of fin and fin base for the passive containment cooling purpose under given conditions, sensitivities of several design factors to the fin length (or fin base length) were preliminarily studied. Further studies will reveal more design constraints and this will affect the optimum design point.

As the next step, the condensation model will be updated and a parametric study will be performed. Also, after considering the heat conduction through the fin and inner structure, the necessary mass of PCM and the corresponding size of container will be obtained. Then, the performance of condenser as the PCCS will be evaluated using the available containment analysis codes.

NOMENCLATURE

A	area [m^2]
c_p	specific heat [J/(kg-K)]
g	gravitational acceleration [m/s^2]
$\overline{h}_L$	average condensation heat transfer coefficient [W/(m^2-K)]
h_{fg}	heat of vaporization [J/kg]
h_{fg}'	modified heat of vaporization [J/kg]
k	thermal conductivity [W/(m-K)]
L	length [m]
$\dot{m}$	condensation rate [kg/s]
Pr	Prandtl number
q	heat transfer rate [W]
Re	Reynolds number
T	temperature [K]
δ	thickness [m]
μ	dynamic viscosity [(Pa-s)]
ρ	density [kg/m^3]
ν	kinematic viscosity [m/s^2]

Subscripts

f	condensate film
l	saturated liquid
sat	saturate
υ	saturated vapor
w	fin

ACKNOWLEDGEMENT

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

REFERENCES

[1] T. L. Schulz, Westinghouse AP1000 Advanced Passive Plant, Nuclear Engineering and Design, Vol. 236, pp. 1547, 2006.

[2] S. H. Bae, T. W. Ha, J. J. Jeong, B. J. Yun, D. W. Jerng, and H. G. Kim, Preliminary Analysis of the Thermal-Hydraulic Performance of a Passive Containment Cooling System using the MARS-KS1.3 Code, Journal of Energy Engineering, Vol. 24, No. 3, pp.96, 2015.

[3] J. S. Park, and S. N. Kim, Design of Passive Containment Cooling System of PWR using Multi-pod Heat Pipe, Transactions of the Korean Nuclear Society Spring Meeting, May 17-18, 2012.

[4] KEPCO & KHNP, Severe Accident Analysis, APR1400-E-P-NR-13003NP, Rev.0, 2013.

[5] B. Young, A. Thiele, A. Fujii, G. Sant, and L. Pilon, Thermophysical properties of phase change materials, UCLA Henry Samueli School of Engineering and Applied Sciences, 2.13.

[6] F. P. Incropera, D. P. Dewitt, T. L. Bergman, and A. S. Lavine, Fundamentals of Heat and Mass Transfer, John Wiley & Sons, New York, NY, USA, 2007.