Thermal Behavior of the Coolant in the Emergency Cooldown Tank for an Integral Reactor

Joo Hyung Moon [a*], Seok Kim [a], Woo Shik Kim [a], Seo Yoon Jung [a], Young In Kim [a]
[a] *Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 34057, Republic of Korea*
[*] *Corresponding author: moonjooh@kaeri.re.kr*

1. Introduction

An opening for SMRs (Small Modular Reactors) grows rapidly and the SMART (System-integrated Modular Advanced ReacTor) developed by KAERI (Korea Atomic Energy Research Institute) has the initiative for the first licensed integral reactor in the world. With an intense support of the Government, the SMART safety enhancement project was successfully finalized resulting in an in-depth development of the most advanced safety features including the Passive Residual Heat Removal System (PRHRS).

The PRHRS is one of the passive safety systems which should be activated after an accident to remove the residual heat from the core and the sensible heat of the reactor coolant system (RCS) through the steam generators until the safe shutdown conditions are reached.

In the previous study [1] presented at the last KNS Autumn Meeting, transient behavior of the RCS temperature and the cooling performance of the PRHRS were investigated numerically by using newly developed in-house code based on MATLAB software. By using the program, the steady-state and transient (quasi-steady state) characteristics during the operation of the PRHRS had been reported. In this program, the temperature of the coolant in the Emergency Cooldown Tank (ECT) was assumed to be constant at saturated state and pool boiling heat transfer mechanism was applied through the entire time domain.

Those assumptions, however, do not reflect the reality precisely. The initial temperature of the coolant contained in the ECT should be balanced with that of the ambient atmosphere in the auxiliary building, where the ECT is facilitated. Upper part of the ECT is open to the air so that the pressure of the ECT maintains the atmospheric pressure.

When the operation of the PRHRS is initiated, the residual heat from the core and sensible heat of the RCS should be delivered through the steam generators and then be removed through the condensation heat exchanger, which is designed to be immersed at all times in the coolant of the ECT. In other words, the ECT plays a role of an ultimate heat sink. Consequently, the temperature of the coolant contained in the ECT starts to increase until it reaches the saturation temperature.

In the present study, the modification and improvement of the program, including development of a subroutine to simulate the variation of the pool temperature of the ECT, will be described and the results of the newly conducted calculations will be introduced. Transient behavior of cooling performance of the PRHRS will clarify the justification of the assumption made in the previous study [1].

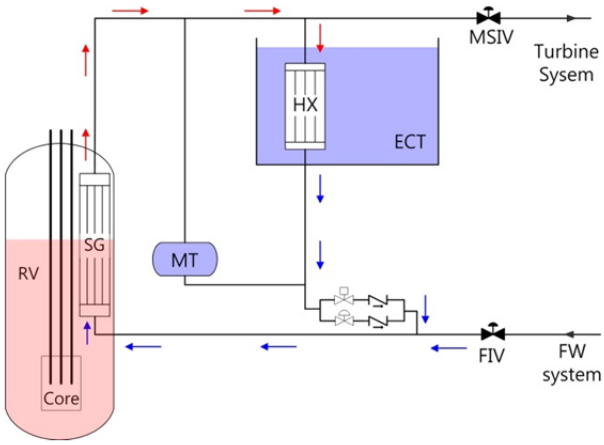

Fig. 1. The schematic of the PRHRS

2. Methods and Results

A graphical representation of the PRHRS is given in Fig. 1. The PRHRS is composed of an emergency cooldown tank, a condensation heat exchanger and a makeup tank. There are four trains of the PRHRS among which three trains are assumed to be available. Each train is connected to a set of two steam generators. When a passive residual heat removal actuation signal (PRHRAS) is given, the main steam isolation valve and feedwater isolation valve are closed automatically. In the closed loop from the steam generator to condensate heat exchanger and vice versa, working fluid gains heat from steam generators but loses it to the coolant of the ECT.

2.1 Condensation Heat Exchanger

The condensation heat exchanger is immersed in the coolant of the ECT. The initial temperature of the coolant contained in the ECT was chosen as 40, 50, 60 and 100℃, respectively for comparison. Hot steam produced from steam generators travels through the condensation heat exchanger and then condensation occurs inside tube wall. Shah [2]'s correlation can be used to predict the heat transfer coefficient inside the tube:

$$h = h_f \begin{Bmatrix} (1-x)^{0.8} \\ + (3.8x^{0.76}(1-x)^{0.04})/(P/P_{cr})^{0.38} \end{Bmatrix}$$
$$h_f = 0.023(k_f/D_i)(GD_i/\mu_i)^{0.8} {Pr_f}^{0.4}. \quad (1)$$

When pool boiling occurs at the outer wall of the tube, Rohsenow [3]'s correlation can be used to predict the heat transfer coefficient outside the tube:

$$q''/\{\mu_f(h_g - h_f)\}\left[\sigma/\{g(\rho_f - \rho_g)\}\right]^{1/2} = {C_{sf}}^{-1/n}\left(C_{P,f}\,\mu_f/k_f\right)^{-(m+1)/n} \times \left\{C_{p,l}(T_{w,o} - T_{sat})/(h_g - h_f)\right\}^{1/n} \quad (2)$$

, where C_{sf}, m and n are 0.013, 0.7 and 0.33, respectively.

On the other hand, when pool boiling does not occur, following natural convection correlations can be employed:

$$\begin{aligned} Nu &= 0.135Ra^{1/3} && for\ Ra > 2 \times 10^7 \\ Nu &= 0.54\ Ra^{1/4} && for\ Ra > 5 \times 10^2 \\ Nu &= 1.18\ Ra^{1/8} && for\ Ra > 2 \times 10^{-3} \\ Nu &= 0.45 && for\ Ra \le 1 \times 10^{-3}. \end{aligned} \quad (3)$$

The choice of correlations between Eqs. (2) and (3) is determined by the following Rohsenow's Onset of Nucleate Boiling (ONB) correlation as given below:

$$T_{w,ONB} = T_{sat}(P) + 0.556\left(\frac{q''}{1082P^{1.156}}\right)^{0.463P^{0.0234}} \quad (4)$$

, where P in bar.

Modeling of steam generator and calculation procedures are basically identical to the previous study [1], which are not duplicated here.

2.2 Results

Fig. 2 shows the temporal behavior of the dimensionless temperature of the RCS. The values of 1.0 in x- and y-axis stand for the safe shutdown conditions. As shown in the figure, after reaching the safe shutdown temperature, the RCS temperature continues to decrease. The discrepancy among results of different initial temperature is not large as noticeable. However, it is evident that the heat removal is rather larger when pool boiling is assumed at the very beginning of the actuation of the PRHRS. This is mainly due to the fact that pool boiling enhances the convective heat transfer.

Fig. 3 shows the temporal behavior of the dimensionless temperature at each position when the ECT is initially at 40℃. Tube wall temperature at both inlet and outlet, ONB temperature and average temperature of the coolant in the ECT were traced with time. As shown in the figure, the pool reached at a saturated state in early time and pool boiling mechanism was dominant for the heat transfer through the condensation heat exchanger. Therefore, it was found that the previous assumption of Moon et al. [1] was acceptable.

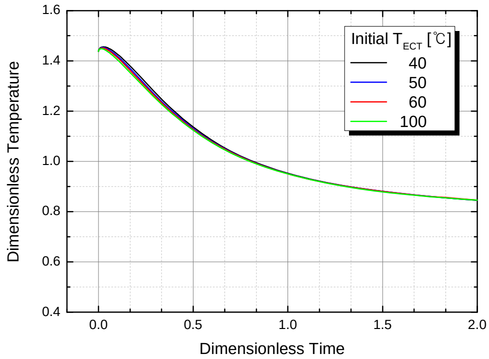

Fig. 2. Temporal behavior of temperature of the RCS for various initial temperature of the ECT

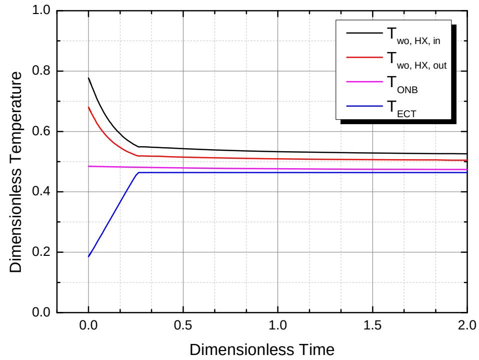

Fig. 3. Temporal behavior of temperature at each position when the ECT is initially at 40℃

3. Conclusions

In the present study, thermal behavior of the coolant of the ECT for PRHRS was analyzed. Pool boiling effect on the RCS temperature was not so large. The coolant of the ECT reached at a saturated state in early time. It was revealed that the assumption made in the previous study [1] was reasonable.

ACKNOWLEDGEMENT

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