Improvement of Emergency Cooldown Tank in terms of long-term cooling

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1. Introduction

SMART(System-integrated Modular Advanced ReacTor)[1] is the earliest licensed SMR in the world, developed by Korea Atomic Energy Research Institute (KAERI). SMART received its Standard Design Approval(SDA) from Korea Government in 2012. After Fukushima accident, passively cooling system of nuclear reactor gets great attention and a consentience reached that at least 72 hours of grace time after an accident should be secured, during which a nuclear reactor remains in safe condition without any operator's intervention.

To meet this requirement, SMART adapted passive cooling system such as passive residual heat removal system(PRHRS). It is composed of an emergency cooldown tank(ETC), a heat exchanger and a makeup tank as shown in Fig. 1. The PRHRS of the fully passive safety system is designed to bring the reactor coolant system to the safe shutdown condition within 36 hours after accident initiation, and to maintain the safe shutdown condition for at least another 36 hours, therefore total 72 hours, without any corrective actions by operators for the postulated design basis accidents.

Even if the ETC contains a large amount of water, the water level goes down as time goes by because the top of the ETC is open to the air. Therefore the ETC should be refilled periodically by auxiliary water supply system in order to use it beyond 72 hours. Otherwise the immersed heat exchanger would be exposed to the air, which would damage the function of PRHRS.

To overcome this shortcoming, installation of an air-cooling heat exchanger at the top of the ETC is proposed as shown in Fig. 2[2]. Here the top of the ETC is now closed. Evaporated steam is collected through the vertical duct and condensed through air-cooling heat exchanger. By natural circulation, water level of ETC can be maintained at steady state for a very long-term period. The purpose of the present study is to investigate the thermal sizing of air-cooling heat exchanger which extends the cooling period of ETC.

2. Methods and Results

2.1 Decay Power

The rate of decay power following the shutdown of a nuclear reactor is obtained from ANS-71 model for the nominal fission products, including the heavy elements and 20% uncertainty. The nominal power of SMART is 330 MWt and the residual power rate at the time of 72 hours after shutdown can be easily calculated as 0.52%.

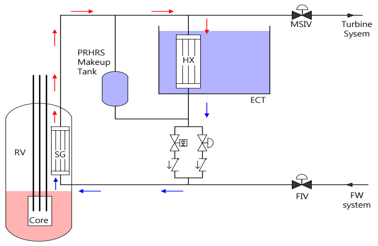

Fig. 1. Schematic of PRHRS of SMART

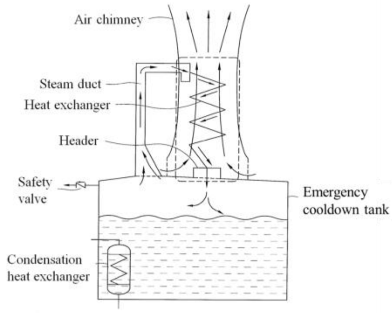

Fig. 2. Improvement of ECT by using air-cooling HX

The PRHRS of SMART consists of four independent trains with a 33% capacity each. It is assumed that one train is not available as initiating event. Therefore each train is supposed to remove the residual heat of 576.7 kW per train.

2.2 Heat Transfer Correlations

In Fig. 2 an air-cooling heat exchanger condensates evaporated steam into water and delivers heat to the ambient air. Assuming that the temperature of tube wall is 100℃ and that of ambient air is 40℃, natural heat transfer coefficient is investigated. A vertical tube is assumed and the tube diameters, *D* are chosen from 1 to 2 inch. The Rayleigh number based on the tube length *L*, Ra_L is larger than 10^9 for the present study, so the turbulent regime was applied.

Churchill and Chu[3] proposed the following correlation for natural convection from a vertical plate:

$$\overline{\mathrm{Nu}_L} = \left[0.825 + \frac{0.387 Ra_L^{1/6}}{\left[1+(0.492/Pr)^{9/16}\right]^{8/27}}\right]^2, \qquad (1)$$

where *Pr* is the Prandtl number. This equation can be applied to vertical cylinders when tube diameter to tube length ratio, *D/L* is larger than $35/Gr^{1/4}$, where *Gr* is the Grashof number. However, it is well known that natural convective heat transfer from vertical slender cylinders and a flat vertical plate can differ significantly because of the transversal curvature effect[4]. McAdams[5] provided an approximate equation for the average heat transfer in turbulent regime:

$$\overline{\mathrm{Nu}_L} = 0.13{Ra_L}^{1/3}. \qquad (2)$$

Eigenson[6] also suggested an empirical equation:

$$\overline{\mathrm{Nu}_L} = 0.148{Ra_L}^{1/3}. \qquad (3)$$

These two equations are reliable in the regime of $4\times10^9 \leq Ra_L \leq 2.5\times10^{10}$. Al-Arabi and Khamis [7] also proposed an experimental average heat transfer correlation for turbulent regime:

$$\overline{\mathrm{Nu}_L} = 0.47{Ra_L}^{1/3}/{Gr_D}^{1/12}, \qquad (4)$$

where Gr_D is the Grashof number based on the tube diameter. Yang[8] established a general correlation for the whole ranges of Ra_L and Pr:

$$\overline{\mathrm{Nu}_L} = \left[0.60\left(\frac{L}{D}\right)^{1/2} + 0.387\left(\frac{Ra_L}{[1+(0.492/Pr)^{9/16}]^{16/9}}\right)^{1/6}\right]^2. \qquad (5)$$

2.3 Heat Transfer Area

Required heat transfer area to remove the residual heat of 576.7 kW per train can be estimated by using above correlations. The number of tubes, N_{tube} is obtained by the following heat balance equation:

$$N_{tube} = Q/[\bar{h}(\pi DL)\Delta T], \qquad (6)$$

where Q is the decay heat, $\bar{h}$ is the average heat transfer coefficient, and ΔT is the temperature difference between the tube wall and the ambient air. Table 1 summarizes the results of 2″ tubes for several models. It is evident that the larger *L/D*, the lesser tubes are required.

Figure 3 shows comparisons among several correlations from 1″ to 2″ tubes. Al-Arabi and Khamis [7] and Yang[8] are in good agreement for high Ra_L regime. Deviation is shown from McAdams[5] and Eigenson[6] because they are specific to the narrow regime of Ra_L. Churchill and Chu[3] gives much higher values, which is inadequate for the present study.

3. Conclusions

Thermal sizing of air-cooling heat exchanger had been investigated by using several heat transfer correlations for natural convection of vertical tubes. Quantitative comparisons were made to find out how many tubes are required to remove the residual heat. This work would contribute to improve the current design of ETC and to extend the cooling period much longer than 72 hours, which will promote the passive safety function of SMART.

Acknowledgement

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Table 1. Required number of 2″ tubes

Models	*L/D*				
	66	77	88	99	110
Churchill & Chu[3]	4726	4073	3580	3194	2884
McAdams[5]	4121	3532	3091	2747	2473
Eigenson[6]	3620	3103	2715	2413	2172
Al-Arabi & Khamis[7]	3328	2887	2496	2219	1997
Yang[8]	3369	2887	2526	2246	2021

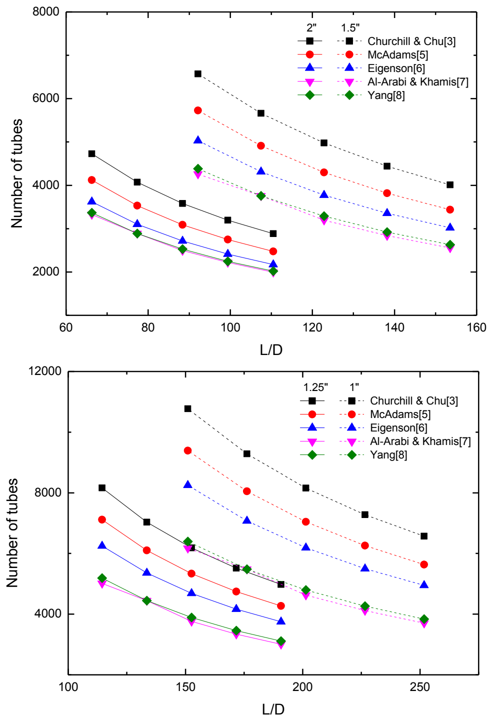

Fig. 3. Comparisons of several models for the number of tubes required.