Transient Performance of Air-cooled Condensing Heat Exchanger in Long-term Passive Cooling System during Decay Heat Load

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1. Introduction

Recently, passive cooling systems have been assigned great importance given their contribution to the safety of nuclear power plants. In the event of a "loss of coolant accident" (LOCA) and a non-LOCA, the secondary passive cooling system would be activated to cool the steam in a condensing heat exchanger that is immersed in an emergency cooldown tank (ECT). Currently, the capacities of these ECTs are designed to be sufficient to remove the sensible and residual heat from the reactor coolant system for 72 hours after the occurrence of an accident. After the operation of a conventional passive cooling system for an extended period, however, the water level falls as a result of the evaporation from the ECT, as steam is emitted from the open top of the tank. Therefore, the tank should be refilled regularly from an auxiliary water supply system when the system is used for more than 72 hours. Otherwise, the system would fail to dissipate heat from the condensing heat exchanger due to the loss of the cooling water. Ultimately, the functionality of the passive cooling system would be seriously compromised. As a passive means of overcoming the water depletion in the tank, Kim *et al.*[1] applied for a Korean patent covering the concept of a long-term passive cooling system for an ECT even after 72 hours. The basic idea behind this concept involves the installation of an air-cooled condensing heat exchanger on the top of the ECT, so that the water level can be maintained by collecting the steam from the tank, as shown in Fig. 1.

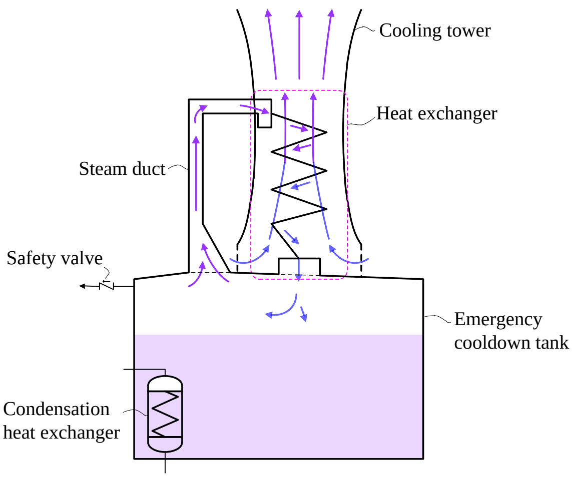


Fig. 1. Schematic of air natural convective cooling system of emergency cooldown tank.

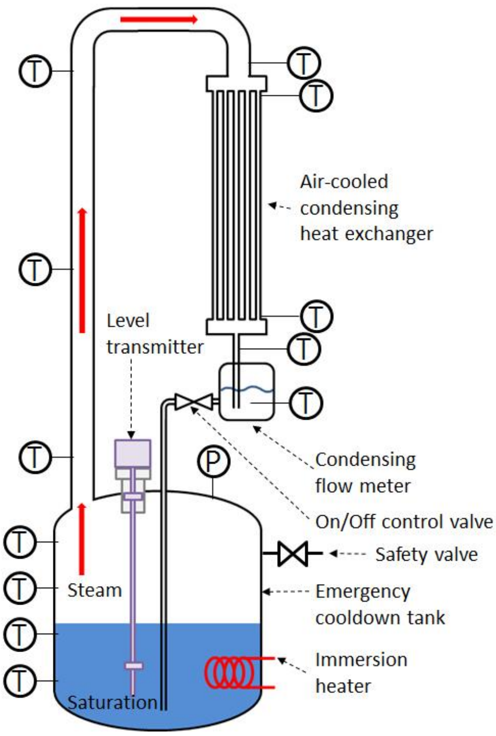


Fig. 2. Schematic diagram of the experimental setup.

In this study, transient performance and scaled design requirement of air-cooled condensing heat exchanger were evaluated by an experimental setup under decay (residual) heat load. Moreover, it was verified that the water level could be maintained even after the long-term operation of passive cooling system (more than 72 hours).

2. Methods and Experiments

2.1 Experimental setup

The schematic diagram of the experimental setup is shown in Figure 2. Figure 2 is a 1/2500 volume scaled model of ECT in the system-integrated modular advanced reactor (SMART). The volumetric capacity of ECT is maximum 0.22 m^3. It was indicated that residual heat after 72 hours is about 0.54% of a normal output in the patent of Kim *et al.*[1]. Therefore, the requirement of cooling capacity of air-cooled condensing heat exchanger is 1.8 MW. Kim *et al.*[2] reported that four independent PRHRS with 50% capacity each remove the core decay heat through natural circulation at any

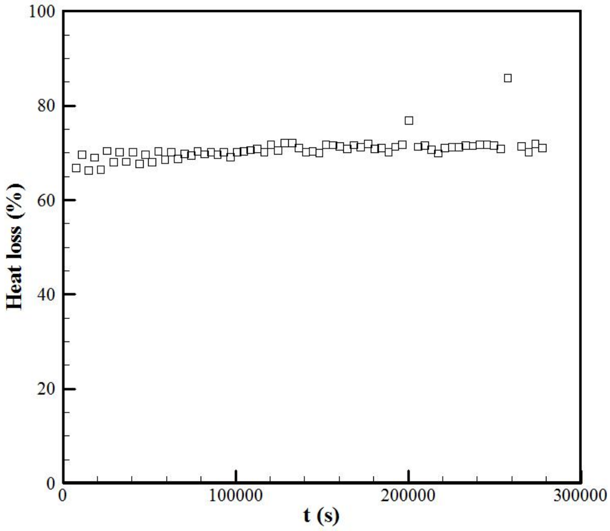


Fig. 3.Heat loss of long-term passive cooling system during decay heat load.

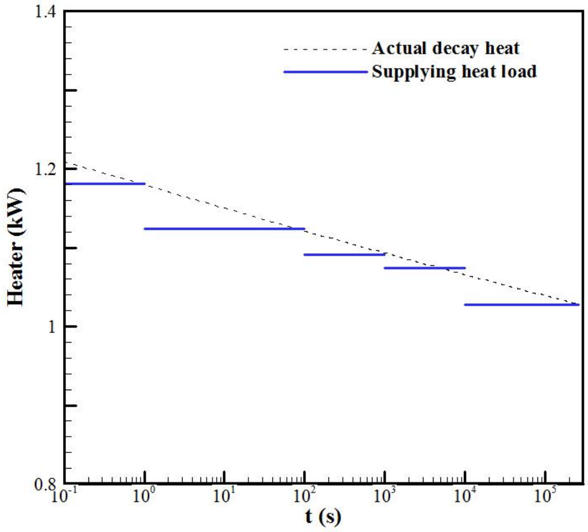


Fig. 4. The actual decay heat and supplying heat load by the electric heater into ECT.

design basis accidents in SMART. Therefore, the required residual heat load and cooling capacity of an air-cooled condensing heat exchanger are 1.1 kW and 0.33 kW in this scaled experiment with applying 70.7% heat loss of the system in Fig. 3, respectively.

The ECT is made of SUS 304L with 4 mm thick plate. The pipe with 2″ outer diameter between the top of the ECT and air-cooled condensing heat exchanger inlet was connected for the evaporating steam path. Air-cooled condensing heat exchanger consists of 25 1/2″ vertical tubes, 1.1 m in the tube length and spaced 0.05 m apart. A level transmitter(HITROL-HT-100RS) was mounted on the top of the ECT. To monitor pressure data, gauge pressure transducer(OMEGA PX01C1-015GV) was mounted on the top of ECT. A safety valve, which prevents system pressure from exceeding the maximum of 1.1 atm, was located at the side of the very top of ECT. An immersion heater (~ 5 kW, OMEGA VTS-3200/240) was mounted at the tank to supply heat into water to simulate condensation heat exchanger of passive cooling system. A programmable AC power supply, which controls heat load according to the event of accident scenario, was connected to the heater. Four of type T sheathed thermocouples were placed at the side of the tank. Five more of type T sheathed thermocouples were places at the side of the 2″ I.D. pipe to measure the steam temperature and enthalpy of both inlet and outlet of the steam cooling heat exchanger. To measure the wall temperatures and natural convective heat transfer coefficient of the air at heat exchanger, two thermocouples were attached to the surface pipe of both ends.

Conventional flow meter (orifice, vortex, rotameter, etc.) is not appropriate to measure very small flow rate of the condensing flow in the steam cooling heat exchanger due to its large loss coefficient. Moreover, its large resistance may prevent the naturally circulating steam flow in the 2″ O.D. pipe. Therefore, a new conceptual device of a flow meter with minimal loss was designed in this experiment [3]. A chamber, which is a volumetric capacity of 525 mL, was manufactured with mounting a water level transmitter and an on/off valve. When the collected condensing water level reaches to the top of the chamber, the on/off valve is open and then the collected water drains into the emergency cooldown tank. After finishing draining water, the on/off valve is closed and the valve opening time is recorded. To prevent pressurizing inside chamber, a tube was installed on the top of the chamber allowing the bypass of the evaporating steam which was not totally cooled down in the steam cooling heat exchanger.

The data acquisition system used in the experiments was a National Instrument cDAQ-9178 eight-slot chassis with an NI9203 analog current input module capable of acquiring 200 kS/s for both the water level transmitter and condensing flow rate, an NI9205 analog voltage input module for the pressure transducer, and an NI9219 12-channel isolated universal AI module for temperature measurement. The measurement frequency was set to 1 Hz. The uncertainty of the natural circulating flow rate and pressure was ± 5.7% of the full scale for the condensing chamber and ± 0.25% of the full scale for the pressure transducer, respectively.

2.2 Experimental procedure

A safety valve on the maximum of 1.1 atm was mounted on the side of the ECT. 0.1 m^3 of water was put into the ECT. Once the AC power supply was turned on, the water started to boil and generate steam, which was initially allowed to mix with the air in the tank for degassing purposes and thus avoid the effects of non-condensing gas. After the steady state had been reached at the heat load of 1.5 kW, we assumed that PRHRS has already been operated for 72 hours. Then, system pressure, temperatures, and condensing flow rate were acquired under the decay heat load given as Fig. 4. An

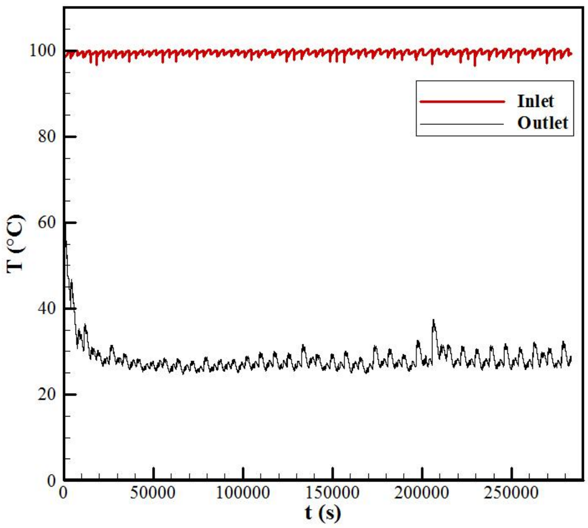


Fig. 5. Flow temperature at both inlet and outlet of air-cooled condensing heat exchanger.

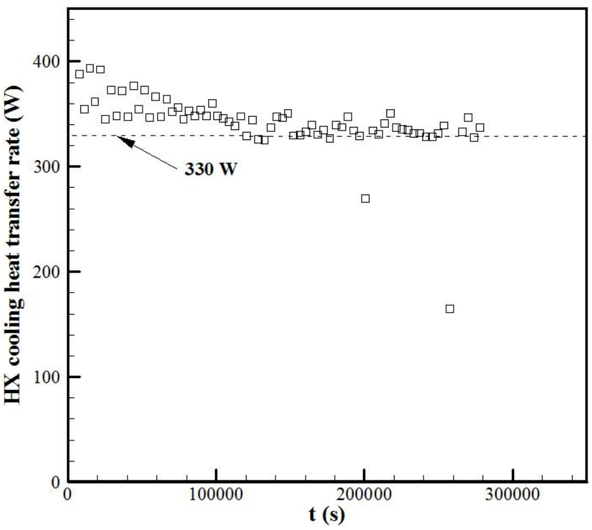


Fig. 6. Transient performance (rectangular symbols) and scaled design requirement (dashed line) of air-cooled condensing heat exchanger under the decay heat load.

arbitrary monomial function was assumed to model a transient decay heat load. The function of transient heating power was rapidly decreased by 21% of the heat load of 1.5 kW until 1 s. After 600 s and 72 hours, it has further dropped to below 1.1 kW and 1.02 kW, respectively.

3. Results

Figures 5 and 6 show the flow temperatures at both the inlet and outlet header and performance of air-cooled condensing heat exchanger under the heat load of Fig. 4. The phase of the inlet flow temperature is a superheated vapor, but approaching the saturation temperature. It was observed that the outlet flow temperature oscillates due to the presence of the condensing flow meter. The magnitude of the oscillation was found to fall with the heat load. The average value of the outlet flow

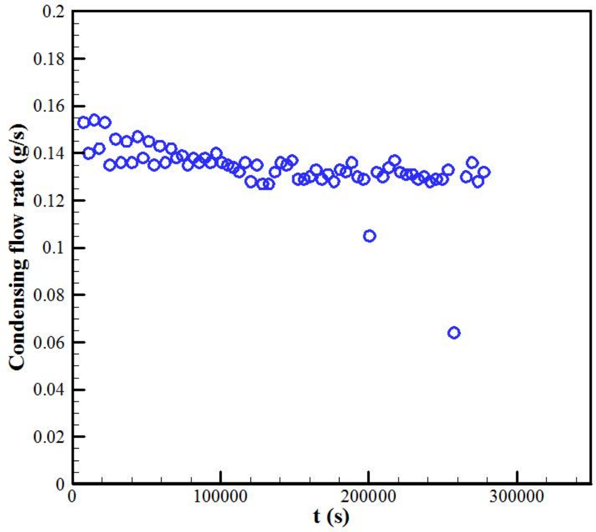
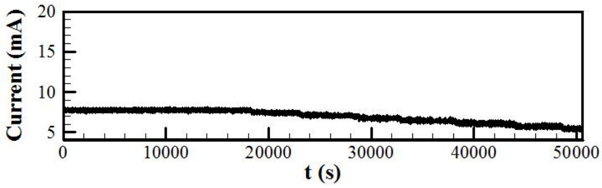
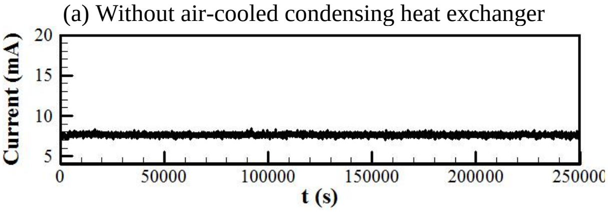


Fig. 7. Measurement of transient condensing flow rate.



(a) Without air-cooled condensing heat exchanger



(b) With air-cooled condensing heat exchanger

Fig. 8 Measurement of current produced by level transmitter in ECT without/with air-cooled condensing heat exchanger.

temperature was 50.7℃ at steady state and 29.8℃ at asymptote line of the given monomial heat load. In Fig. 6, the cooling capacity was initially 0.395 kW and gradually decreased to be 0.33 kW at the transient heat load of Fig. 4, thus satisfying the scaled design requirement of cooling capacity of an air-cooled condensing heat exchanger of 0.33 kW.

Figure 7 shows condensing mass flow measurement as time goes on. The condensing flow rate was 0.155 g/s at steady state and approached to 0.135 g/s at the end of heat load. When the heat load decreases, the condensing mass flow rate also decreases based on the following equation:

$$\dot{Q}_{cond} = \dot{m}_{cond}(i_{in} - i_{out}) \quad (1)$$

Figure 8 shows water level of the ECT without/with installing air-cooled condensing heat exchanger. The output from this transmitter is a signal of between 4 and 20 mA, corresponding to the position of the float of the level indicator. Before testing, the level transmitter was calibrated according to the amount of water in the tank. The volumetric amounts of water corresponding to signals of 4 and 20 mA were found to be 0.0636 m^3 and 0.227 m^3, respectively. The water level increases linearly between the two ends of the scale. The signal was found to be 7.56 mA when there was 0.1 m^3 of water inside the tank. With opening the top of ECT, the amount of water remaining is estimated as 0.074 m^3 which corresponds to 5 mA after about 11 hours. It will be definitely depleted after 72 hours. In Fig. 8(b), however, a water volume of about 0.1 m^3 is maintained by the collection of the steam in the air-cooled condensing heat exchanger during the long-term operation of the passive cooling system even after 72 hours. Therefore, it was verified by experiment that the water level in the ECT is maintained by refilling it with condensed water even after the long-term operation of the passive cooling system.

4. Conclusions

This study presents transient performance of ECT with installing air-cooled condensing heat exchanger under decay heat load. The cooling capacity of an air-cooled condensing heat exchanger was evaluated to determine its practicality. It was changed from 0.39 to 0.33 kW which is sufficient to satisfy the scaled design requirement. Moreover, it was verified by experiment that the water level in the ECT is maintained by refilling the evaporating steam in the air-cooled condensing heat exchanger, while it could be gradually depleted after 72 hours without installing it or without refilling by active means. Therefore, this study clearly verified the promise of the concept of a long-term passive cooling system for application to an ECT.

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