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Natural convective heat transfer of air to steam counter flow heat exchanger for long-term passive cooling system

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1. Introduction

Passive cooling system of nuclear reactor became highly significant after Fukushima accident occurred. Many nuclear reactors adopt the passive cooling system. One of the passive cooling systems is called passive residual heat removal system(PRHRS), which is composed of an emergency cooldown tank(ECT) and condensation heat exchanger that is submerged in the ECT to cool down the steam from steam generator. However, the water as a coolant of the ECT is depleted by evaporation when it is operated for a long time. Therefore, Kim *et al.* [1] tested feasibility of the concept of a long-term passive cooling system for the ECT. They proved that when they installed and operated an air-cooled heat exchanger on top of the ECT, evaporated steam condensed into water so the ECT has maintained water level over 72 hours. Additionally, they measured average natural convective heat transfer coefficient as well. However, due to the structural reason, they could not measure local natural heat transfer coefficient. It had to be natural convective heat transfer, but if a thermocouple is installed in the middle of the heat exchanger tube, the thermocouple wire disturbed the flow of the air. Thus, they used the average temperature of tube inlet and outlet.

In this study, local natural convective heat transfer coefficient was measured experimentally. It was measured at the inside surface of tube side.

2. Methods and Results

For the experiment, air-cooled condensing heat exchanger was installed on the upper part of the ECT.

2.1 Experimental Setup

The schematic diagram is demonstrated in Fig. 1. It is a 1/2500-volumed scaled-down model of the ECT of System-integrated modular advanced reactor (SMART). The volume of the ECT is 0.22 m^3, which is made of 4mm-thick SUS 304L. A pipe with 2-in (50.8 mm) is connected between the inlet of the top of the ECT and air-cooled condensing heat exchanger. It is designed to decrease the flow resistance of the evaporating steam. Air-cooled condensing heat exchanger is made from 2 tubes whose inner diameter of the tube is 261.4 mm and outer diameter is 318.5 mm. Flow of steam and air is demonstrated in Fig.2. Steam flows in the shell side from top to bottom, while air flows in the opposite direction in the tube side so that steam can be cooled down and flow into condensing flow meter. Since the thermocouple and its wire do not pass the tube side, this enables the airflow not to be disturbed by the thermocouple wires. The length of the tube is 1.8 m. When the condensing flow meter is filled with condensate, on/off control valve opens and let it out back to the ECT. After this process, valve remains open further for 4 seconds to ensure that the condensate is fully out. The concept of the flow meter was proposed by Kim *et al.* [2] as the condensing flow rate is too small to measure with conventional flow meters by an orifice, vortex or rotameter and so on. There are 21 thermocouples used to measure temperature. Among them, 5 are located inside of the ECT to check the inside temperature of the ECT, 1 for inlet of the 2-in steam pipe (outlet of the ECT) and another 1 for outlet of it (inlet of the heat exchanger) to check the steam

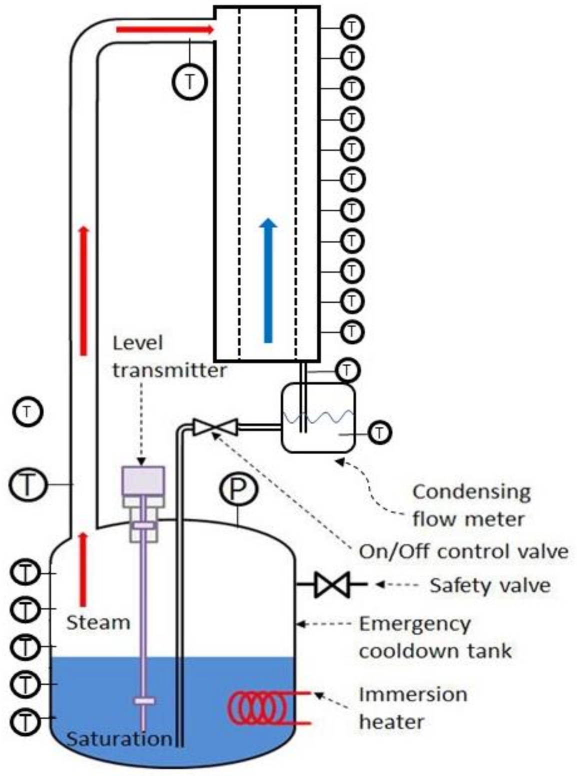

Fig. 1. Schematic diagram of Experimental setup.

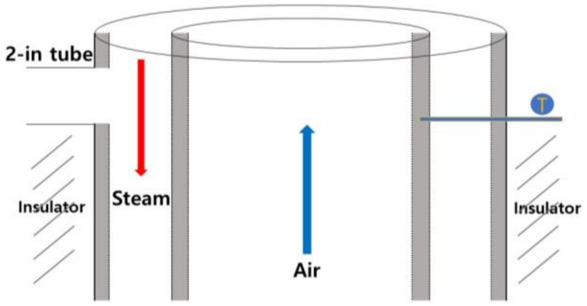

Fig. 2. Demonstrations of steam and air flow, and location of thermocouple.

temperature. 11 (OMEGA TMQSS-125U-6) are installed along the heat exchanger spaced 0.15 m apart. Another one is located in the 1/2-in pipe that is connected to outlet of the heat exchanger, 1 in the condensing flow meter to observe condensate and 1 for ambient temperature, respectively. The data was observed by data acquisition system of Yokogawa SMARTDAC+ GM10 module with three GX90XA-10-U1N analog universal input modules with 10 channels and one GX90XA-10-C1N analog DC current module. The frequency of measurement was set to 1 Hz.

2.2 Experimental procedure

Experimental procedure is same with Kim *et al*. [1]. 1.2 kW, 1.3 kW, 1.4 kW were chosen for residual heat loads for the experimental conditions. They were determined from the experimental results that any heat load less than 1 kW did not let the water in the ECT boil. On the other hand, heat load over 1.5 kW resulted in incomplete condensation so could not get any meaningful data.

2.3 Performance test

Performance test was carried out first. Cooling capacity $\dot{Q}$ was calculated as follows:

$$\dot{Q} = \dot{m}(i_{in} - i_{out}) \tag{1}$$

, where $\dot{m}$, i_{in} and i_{out} are mass flow rate, enthalpy of heat exchanger inlet and outlet, respectively. Table I contains calculated cooling capacity, heat loss and mass flow rate. Heat loss from the ECT was 31% on average of the heat loads of 1.2, 1.3, 1.4 kW. Cooling capacity were 0.77 kW, 0.89 kW and 1.06 kW at the heat loads of 1.2 kW, 1.3 kW, 1.4 kW each. Mass flow rate was obtained from the volume of condensate flowed out from the condensing flow meter that had volume of 680 mL on average and operating time interval of on/off control valve.

Table I: Cooling capacity, heat loss and condensing mass flow rate of air-cooled shell and tube condensing heat exchanger.

Heat load (kW)	Cooling capacity (kW)	Heat loss (%)	Mass flow rate (g/s)
1.2	0.77	36	0.30 ± 0.01
1.3	0.89	32	0.36 ± 0.01
1.4	1.06	24	0.46 ± 0.04

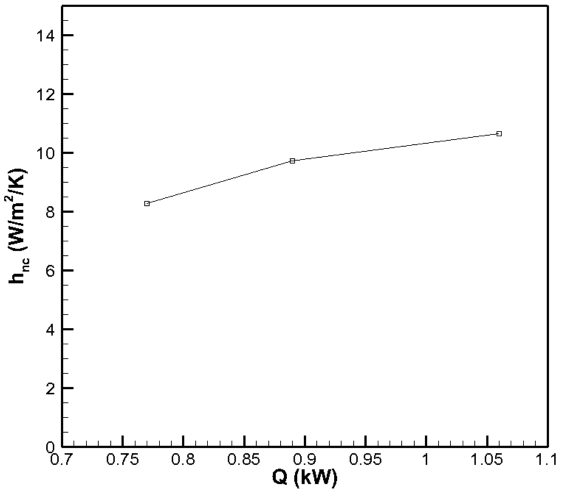

Fig. 3. Natural convective heat transfer coefficient of air-cooled heat exchanger.

2.4 Natural convective heat transfer coefficient

To obtain natural convective heat transfer coefficient, temperature of heat exchanger surface was used. As mentioned in 2.1, temperatures of 11 nodes of air-cooled heat exchanger were measured. From the data, the heat transfer coefficient h_{nc} was calculated as follows:

$$h_{nc} = \frac{Q}{\pi \cdot D_{in} \cdot 0.15(T_s - T_{amb})} \tag{2}$$

, where D_{in} is inner diameter of the heat exchanger tube, constant 0.15 means interval of each thermocouples, T_s is surface temperature of the heat exchanger and T_{amb} is ambient temperature. The obtained values are shown in Fig. 3. As heat load increases, convective heat transfer coefficient increases as well.

3. Conclusions

In this study, natural convective heat transfer coefficient was measured. To get surface temperature of air-cooled heat exchanger without any disturbance, steam flows in the shell side but air flows in the tube side. According to the result using the surface temperature, convective heat transfer coefficient increases in accordance with increase of heat load. Based on this result, it is necessary to compare with the correlations in the future.

REFERENCES

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[2] M. J. Kim, J. H. Moon, Y. Bae, Y. I. Kim, H. J. Lee and K. K. Kim, Measuring Device for Micro Flow Rate and Nuclear Power Plant Having the Same, Korea Patent No. 10-1644060, 2016.