Sensitivity analysis of condensation and air natural convection coefficients of air-cooled condensing heat exchanger of emergency cooldown tank in long-term passive cooling system

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1. Introduction

When an accident occurs in nuclear reactor, passive cooling system is activated to cool down a huge amount of steam in heat exchanger immersed into emergency cooldown tank, which is depleted by evaporation eventually. However, the passive cooling system is able to be operated for a long time by collecting the evaporated steam using an air-cooled condensing heat exchanger. Kim *et al.* [1] conducted an experiment to measure condensing flow rate, cooling capacity of an air-cooled condensing heat exchanger, and average air natural convection coefficient of long-term passive cooling system. They verified the promise of the concept of a long-term passive cooling system for application to an emergency cooldown tank.

Both condensation heat transfer and air natural convection coefficient should be a great concern to an air-cooled condensing heat exchanger. Lee *et al.* [3] investigated the existing condensation heat transfer correlations for the design of a heat exchanger inside a pool. The improved Shah's correlation [2] showed most satisfactory results for the heat transfer coefficient and mass flow rate in water pool in the absence of non-condensable gas. Moreover, Ju *et al.* [4] expanded the research of Lee *et al.* [3] as a heat exchanger for both inside a pool and a cooling jacket(forced convection). They also concluded that the improved Shah's correlation [2] showed most satisfactory results for condensation heat transfer coefficient with 34.8% average error by using 1,157 experimental data points.

In this study, cooling performance of air-cooled heat exchanger and average heat transfer coefficient around a circular tube of the heat exchanger were measured experimentally. Moreover, local condensation heat transfer coefficient was predicted by an in-house thermal sizing program of condenser and then compared with the existing condensation heat transfer correlations using experimental data. Consequently, a condensation heat transfer correlation was suggested for the design of air-cooled condensing heat exchanger of emergency cooldown tank in long-term passive cooling system.

2. Methods and Results

2.1 Thermal sizing program of condensers

A thermal sizing program of air-cooled condensing heat exchanger was developed by KAERI (Korea Atomic Energy Research Institute) [4]. The program solves one-dimensional steady continuity, momentum and energy equations together by segmentizing 101 nodes of a heat exchanger tube as shown in Fig. 1. After assuming initial local heat load, condensation part of the tube length is calculated. The geometry of heat exchanger, such as length, diameter, and thickness, and inlet conditions, mass flow rate and steam temperature, are given. Total pressure is assumed to be constant through the tube by neglecting pressure drop. Condensing tube length and node number (j_{CB}), condensing boundary of the tube, are decided by energy balance as follows:

$$\Delta Q = \dot{m}_{g,j} i_{g,j}\left(T_{bulk,j}, P_{total}\right) - \dot{m}_{g,j+1} i_{g,j+1}\left(T_{bulk,j+1}, P_{total}\right) \quad (1)$$

Then, condensation heat transfer coefficient, h_{in} and inner wall temperature, $T_{w,in}$ were iterated until satisfying the given heat load. Condensation heat transfer coefficient was needed to calculate inner wall temperature in each node. Corresponding inner wall temperature of the tube at each node is calculated by the given condensation heat transfer coefficient as follows:

$$q'' = h_{in}(T_{w,in} - T_{bulk}) \quad (2)$$

Outer wall temperature of the tube, $T_{w,out}$ is calculated by one dimensional tube conduction equation in each node as follows:

$$q'' = 2k_w \frac{T_{w,in} - T_{w,out}}{D_{in} \ln\left(D_{out}/D_{in}\right)} \quad (3)$$

Outside the tube, for air natural convection coefficient, Kim *et al.* [1] measured average natural convection coefficient. They concluded that the Al-Arabi and Khamis [5] model produced a satisfactory prediction of the natural convective heat transfer coefficient with the average error of 9%. Air natural convection coefficient, measured by Kim *et al.* [1], was adopted in this program.

Calculated condensing tube length by the given air natural convection coefficient is compared to the initially calculated tube length. If they are not same, the inner wall temperature will be iterated. Then, the original heat load up to satisfy overall heat transfer rate is calculated iteratively. At the single phase part of the tube length after fully condensation in the tube, the same procedure as condensation part is applied. However, the

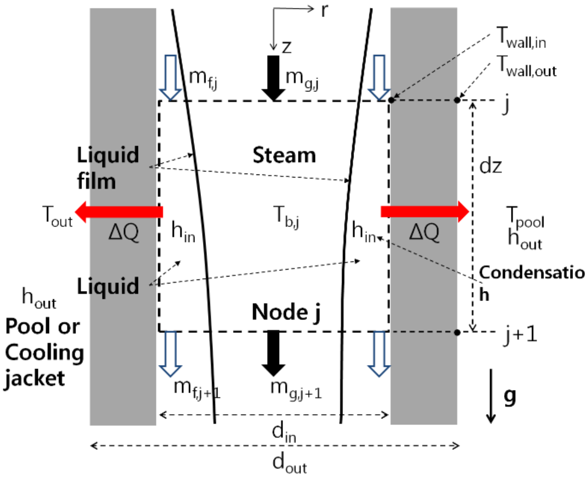

Fig. 1. Schematic of a discretized node of a vertical tube in a condensation heat exchanger [4]

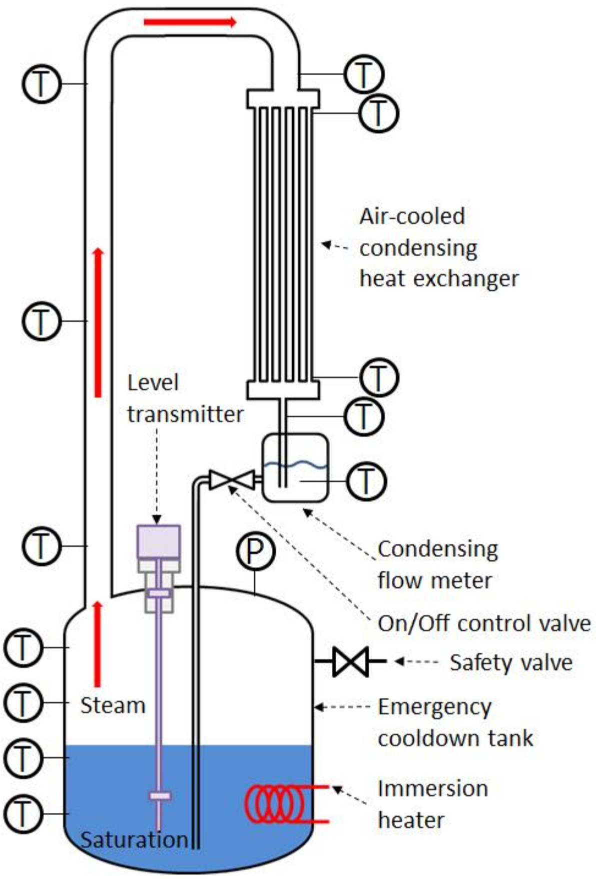

Fig. 2. System diagram of experimental setup [1]

Dittus-Boelter equation is used to calculate inside heat transfer coefficient instead of condensation heat transfer correlation.

$$h = 0.023\left(\frac{k_f}{D}\right)\left(\frac{GD}{\mu_f}\right)^{0.8} \mathrm{Pr}_f^{0.4} \quad (4)$$

ASME steam table was used to obtain water properties.

2.2 Experiments

Kim et al. [1] conducted an experiment on the passive cooling system of an emergency cooldown tank to test the feasibility of the concept of long-term passive cooling, that is, naturally circulating steam and the maintenance of the water level in the emergency cooldown tank as shown in Fig. 2. Kim et al. [6] suggested that diameter and effective length of a straight tube are 10 ~ 30 mm and 1 m for 5 W/m^2/K air natural convection coefficient and 40°C ambient temperature, respectively. The corresponding tube pitch is the same as double tube diameter. Therefore, the diameter and length of a tube were selected as half-inch and 1.1 m in the experiment.

Moon *et al.* [7] conducted a thermal sizing of the vertical tubes in an air-cooled condensing heat exchanger, using established natural convective heat transfer correlations with the input data of Kim *et al.* [1]. Their calculations estimated that 25 half-inch tubes would be sufficient to cool a residual heat load after 72 hours from the reactor shutdown. Therefore, the air-cooled condensing heat exchanger consists of 25 half-inch vertical tubes (arranged in a 5 × 5 array), 1.1 m in length and spaced 0.05 m apart. Two thermocouples were placed at the inlet and outlet headers of the air-cooled condensing heat exchanger to measure the flow temperature and enthalpy difference of both the inlet and outlet. Two thermocouples were attached to the surface of both ends of the center tube to measure the outer surface temperature and average natural convective heat transfer coefficient of the air, without disturbing the induction of the natural air flow.

2.3 Results

Average condensation heat transfer coefficient was obtained by the thermal sizing program with the experimental conditions and data [1] shown in Table I. On the other hand, Ju et al. [4] evaluated the thermal sizing program with the existing experimental data of Khun [8] and Lee [9] for the case of a tube inside cooling jacket. They concluded that Shah's [10] and the improved Shah's [2] correlations satisfactorily predicted the experimental data of Khun [8] and Lee [9] with an average error of 25% and 44%, respectively. Therefore, two condensation correlations, Shah [10] and the improved Shah [2], were selected to compare average condensation heat transfer coefficient with current experimental data.

TABLE I. Experimental data of air-cooled condensing heat exchanger (Saturated inlet and 63% heat loss in the system)

$\dot{Q}$ (kW)	$\dot{m}_{cond}$ (g/s)	T_{out} (°C)	h_{out} (W/m^2/K)
0.39	0.15	24.4	8.98
0.51	0.19	34.4	10.26
0.54	0.22	50.7	10.08

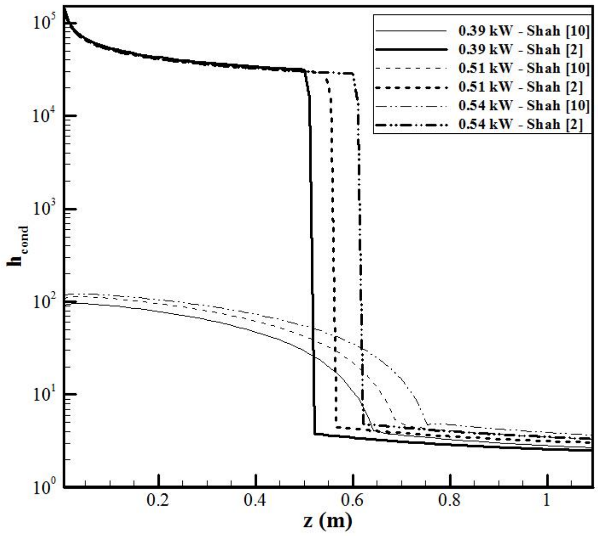

Fig. 3. The comparison of the correlations of condensation heat transfer to the experimental data of Kim *et al.* [1]

TABLE II. Comparison of outlet temperature measured by experiment and predicted by two condensation correlations (Shah [10] and Shah [2])

$\dot{Q}$ (kW)	Condensation correlations	T_{out} (℃)	
		Prediction	Experiment
0.39	Shah [10]	33.5	24.4
	Shah [2]	40.2	
0.51	Shah [10]	36.0	34.4
	Shah [2]	44.2	
0.54	Shah [10]	40.0	50.7
	Shah [2]	49.6	

2.3.1 Comparison of the existing condensation heat transfer correlations

Figure 3 shows the predictions of local condensation heat transfer coefficient with both Shah's [10] and the improved Shah's [2] condensation correlations at the cooling capacity of 0.39, 0.51, and 0.54 kW. As the cooling capacity increases, the position, where the local quality is zero, moves back to the end of the tube. In the condensing region, the improved Shah's correlation [2] predicted condensation heat transfer coefficient about the order of 100 magnitudes larger than Shah's correlation [10]. Such a large heat transfer coefficient brings about fully condensation quickly.

Since the local condensation heat transfer coefficient was not experimentally measured, outlet temperature was compared with the data calculated by the thermal sizing program with two correlations in Table II. Both Shah and the improved Shah correlations over-predicted the experimental outlet temperature about 10℃ larger. This error was not caused by the accuracy of condensation correlation itself, but by the average value of air natural convection coefficient. Despite of the error, the improved Shah's correlation [2] shows the best predictor of the experimental data intuitively.

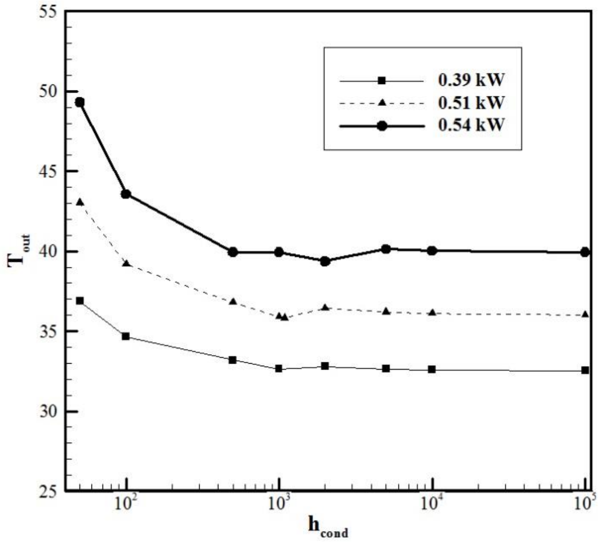

Fig. 4. Outlet temperature vs. average condensation convection coefficient with the experimental data of Kim *et al.* [1]

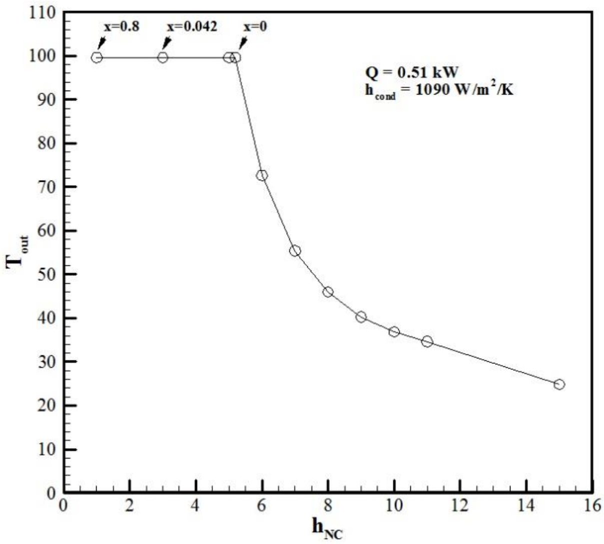

Fig. 5. Outlet temperature vs. average air natural convection coefficient at Q = 0.51 kW and h_{cond} = 1090 W/m^2/K

2.3.2 Effects of both condensation and air natural convection coefficient

The average condensation heat transfer coefficient was reduced by the thermal sizing program at the given experimental condition in Table I. As a result, average condensation heat transfer coefficients at the cooling capacity of 0.39, 0.51, and 0.54 kW were 2600, 1090, and 44 W/m^2/K, correspondingly. Figure 4 shows the sensitivity analysis result while changing average condensation heat transfer coefficient from 50 to 10^5 W/m^2/K with fixing the experimental air natural convection coefficient. Above the average condensation heat transfer coefficient of 10^3 W/m^2/K, outlet temperature did not change significantly, indicating that condensation heat transfer does not play a big role to design air-cooled condensing heat exchanger.

Figure 5 shows the sensitivity analysis result of air natural convection coefficient at the cooling capacity of 0.51 kW and average condensation heat transfer coefficient of 1090 $W/m^2/K$.

As air natural convection coefficient increases, the outlet temperature decreases significantly.

3. Conclusions

For the purpose of the design air-cooled condensing heat exchanger of emergency cooldown tank in long-term passive cooling system, condensation heat transfer coefficient was reduced by thermal sizing program from the experimental data of Kim *et al.* [1] and compared to the existing condensation heat transfer correlation. In addition, a sensitivity analysis of both condensation and air natural convection coefficients was performed in this study. The main conclusions are:

1. From the investigation of the existing condensation heat transfer correlation to the experimental data of Kim *et al.* [1], the improved Shah's correlation [2] showed most satisfactory results.

2. Average condensation heat transfer coefficients at the cooling capacity of 0.39, 0.51, and 0.54 kW were obtained as 2600, 1090, and 44 $W/m^2/K$, correspondingly. The error may be caused by the inaccurate average measurement of air natural convection coefficient.

3. While changing average condensation heat transfer coefficient from 50 to 10^5 $W/m^2/K$ with fixing the experimental air natural convection coefficient, condensation heat transfer did not affect the design of air-cooled condensing heat exchanger over 10^3 $W/m^2/K$.

4. Air natural convection coefficient significantly affects the design of air-cooled condensing heat exchanger. Therefore, more accurate and locally measured air natural convection coefficient should be required for the future work.

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