Numerical Study on the Design Concept of an Air-Cooled Condensation Heat Exchanger in a Long-term Passive Cooling System

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1. Introduction

SMART (System-integrated Modular Advanced ReacTor) is an integral reactor [1] developed by the Korea Atomic Energy Research Institute (KAERI). She can produce 100 MW of electricity, or 90 MW of electricity and 40,000 tons of desalinated water concurrently, which is sufficient for 100,000 residents.

SMART is the only licensed SMR in the world since the Nuclear Safety and Security Commission (NSSC) issued officially the Standard Design Approval (SDA) on 4 July 2012. Recently, the pre-project engineering (PPE) was officially launched for the construction of SMART and developing human resources capability. Both KAERI and King Abdullah City for Atomic and Renewable Energy (K.A. CARE) will conduct a three-year preliminary study to review the feasibility of building SMART and to prepare for its commercialization.

Since the Fukushima accident, the passive cooling systems of nuclear reactors have received a great amount of attention. SMART is equipped with passive cooling systems in order to enhance the safety of the reactor. The PRHRS (Passive Residual Heat Removal System) is the major passive safety system, which is actuated after an accident to remove the residual heat and the sensible heat from the RCS (Reactor Coolant System) through the steam generators (SGs) until the safe shutdown condition is reached.

The PRHRS for the SMART design utilizes an emergency cooldown tank (ECT) as a heat sink. The residual heat is transferred to the water in the ECT. The current ECT can remove the residual heat for at least 72 hours. However, the passive cooling system is required to improve the inherent safety and reliability of nuclear power plant more effectively. For the long-term passive cooling system, Kim *et al*. [2] proposed to install and air-cooled condensation heat exchanger on top of the ECT. The water inventory in developed ECT should be periodically refilled from air-cooled heat exchanger. Experimental studies were conducted for long-term passive cooling system by performing an energy balance test with a scaled-down experimental setup by Kim *et al*. [3]. Figure 1 shows an experimental setup. It was determined that a naturally circulating steam flow can be used to refill the tank. However, an experimental validation for the air-cooled condensation heat exchanger is required.

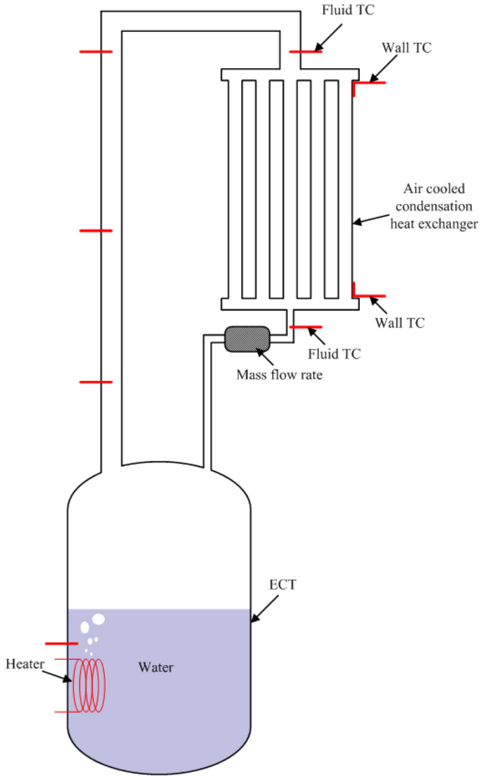

Fig. 1. Schematic diagram example of the experimental setup from Kim *et al*. [3]

In this study, condensing heat transfer correlation of TSCON is evaluated with the Kim *et al.* [3]'s data set to design an air-cooled condensation heat exchanger without noncondensable gas effect in a long-term passive cooling system.

2. Numerical Study

2.1 Thermal Sizing Program TSCON

TSCON solves one-dimensional steady continuity, momentum and energy equations together by nodalizing a tube. After assuming initial tube length and mass flow rate from experimental data, condensation part of the tube outlet temperature and cooling capacity are decided. Also, assuming initial tube length and outlet temperature from experimental data, the mass flow rate and cooling capacity of an air-cooled condensation heat exchanger are calculated. Total pressure is assumed to be constant throughout the tube. Inner wall temperature

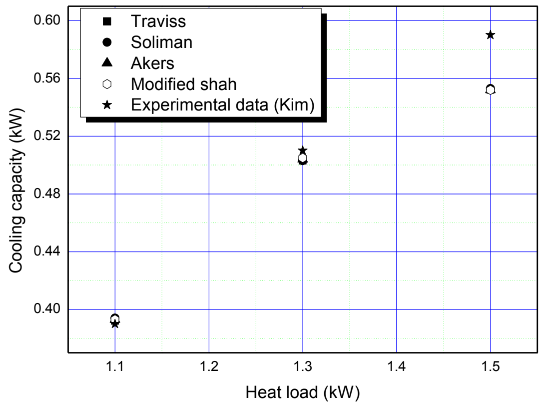

Fig. 2. The comparison of the following four correlations of cooling capacity to the experimental data at assuming the initial mass flow rate

Table I: Error of experimental cooling capacity compared with the four correlations at assuming the initial outlet temperature

Heat load (kW)	1.1	1.3	1.5
Traviss [8] (%)	N/A	5.6	8.8
Soliman [7] (%)	N/A	4.9	9.8
Akers [6] (%)	N/A	4.3	11.3
Modified Shah [9] (%)	N/A	2.7	11.8

of the tube at each node is calculated using a condensation heat transfer correlation. Outer wall temperature of the tube is calculated by solving one dimensional tube conduction equation. Tube length calculated by the outside pool boiling heat transfer coefficient is compared to the previously obtained one. If they did not match with each other, the inner wall temperature shall be iterated. The original heat load is also iterated to satisfy overall heat transfer rate. Then, the same procedure applies to single phase part of the tube. To predict the heat transfer coefficient inside the tube, the existing condensation correlation was adopted for condensation section and the Dittus-Boelter correlation was applied for single phase section. To predict the heat transfer coefficient outside the tube, a natural convective heat transfer correlation on a cylinder is used for an air cooling [4]. Air properties of thermal expansion coefficient for the Grashof and the Prandtl number were obtained from the NIST database [5].

2.2 Existing condensation correlations

Most the correlations are proposed for horizontal tubes and none of well-validated correlations for vertical tubes was found. Shah's correlation can be applied to vertical tubes. Since gravitational liquid film effect cannot be negligible, it is appropriate that a condensation correlation in a vertical tube is selected. However, the following four existing condensation correlations were chosen to validate TSCON: Akers (1959) [6], Soliman (1968) [7], Traviss (1973) [8], and the improved Shah correlation (2009) [9].

3. Results

Figure 2 shows the comparison of cooling capacity between TSCON predictions using the four existing correlations and experimental data. The four existing correlations can predict the cooling capacity very accurately at 1.1 kW and 1.3 kW heat load. However, the four correlations underestimate the cooling capacity at 1.5 kW heat load.

Table 1 shows the error of cooling capacity experimental data compared with four correlations at assuming the initial outlet temperature. The modified Shah correlation gives the best prediction of the cooling capacity experimental data at 1.3 kW heat load. However, the Traviss's correlation is the best predictor for cooling capacity at 1.5 kW heat load. Most of the condensation correlations predicted the measured cooling capacity within the error of 11.8%.

4. Conclusions

In this study, condensing heat transfer correlations in TSCON were validated using experimental data. It was shown that most of the condensation correlation gave satisfactory predictions of the cooling capacity of an-air cooled condensation heat exchanger.

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