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Transient performance of air-cooled condensing heat exchanger in long-term passive cooling system under decay heat load

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ABSTRACT

The transient performance of an air-cooled condensing heat exchanger in a long-term passive cooling system was evaluated under a decay heat load modeled by the ANS-73 curve. An experiment was conducted in a 1/2500-volume scaled-down model of the emergency cooldown tank (ECT) of the system-integrated modular advanced reactor (SMART). It was confirmed that the scaled design requirement of cooling capacity of the air-cooled condensing heat exchanger was well satisfied under the decay heat load. It was also confirmed that the water level in the emergency cooldown tank was maintained continuously for longer than 72 h by the collection of steam in the air-cooled condensing heat exchanger under the decay heat load.

1. Introduction

An emergency cooldown tank (ECT) is used as a heat sink, which dissipates residual heat in the passive cooling system of an integral nuclear reactor—the system-integrated modular advanced reactor (SMART)—upon occurrence of an accident. Currently, the capacities of the ECT of SMART are designed to be sufficient to remove the residual heat from the reactor coolant system for 72 h after the occurrence of an accident. However, cooling water should be periodically refilled into the ECT in order for it to be operable after 72 h, because the water level in the ECT decreases with time by evaporation, as steam is emitted from the open top of the tank. Therefore, Kim et al. (2013) applied for a United States patent covering the concept of a long-term passive cooling system for an ECT. The basic concept of this system is based on the installation of an air-cooled condensing heat exchanger on top of the ECT so that the water level can be maintained by collecting the steam from the tank as shown in Fig. 1. Then, Kim et al. (2015) conducted an energy balance experiment under a steady heat load for 7 h in a 1/2500-volume scaled-down model of the ECT of SMART. They observed the existence of naturally circulating steam flow and verified that the water level in the ECT was maintained for over 7 h of operation of the passive cooling system by installing an air-cooled condensing heat exchanger.

In reality, however, the events of operating condition and the decay head load should vary with time when the passive cooling system starts operating. Therefore, the transient performance of an air-cooled condensing heat exchanger in a long-term passive cooling system under a transient decay heat load in the ECT needs to be investigated.

Many researchers have investigated the transient performance of a wide variety of types of heat exchangers and under various operating conditions. For example, Gartner and Harrison (1965) experimentally studied the transient performance of a fin-tube water-to-air cross-flow heat exchanger under periodic variations of the fluid inlet temperature. Further, several analytical and numerical modeling methods have been developed for analyzing the dynamic behavior of cross-flow heat exchangers. Roetzel and Xuan (1992) studied a method for predicting the transient responses of multipass shell-and-tube heat exchangers with an arbitrary number of tube side passes to arbitrary inlet temperature changes. The inlet temperature changes may occur on either side or simultaneously on both sides. Guellal and Abdesselam (2009) studied the time lag of a double-pipe heat exchanger operating with variable flow rates. They proposed an empirical method for the prediction of this parameter when a double-pipe heat exchanger is subjected to a flow rate step at the entrance. Experimental data were used for developing correlations for both hot and cold fluids. The transient behavior of coupled heat exchangers subjected to sudden changes in inlet temperature was studied experimentally and analytically by Asgharpour et al. (2013). They demonstrated that the analytical model has high accuracy and can

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Nomenclature

A	area [m^2]	*Subscripts*	
h	heat transfer coefficient [$W/m^2/K$]	∞	ambient
i	enthalpy [J/kg]	*cond*	condensation
$\dot{m}$	mass flow rate [kg/s]	*in*	inlet header
N	the number of tubes	*NC*	natural convection
$\dot{Q}$	heat load [W]	*out*	outlet header
T	temperature [°C]	*s*	tube surface
t	time [s]	*trip*	trip

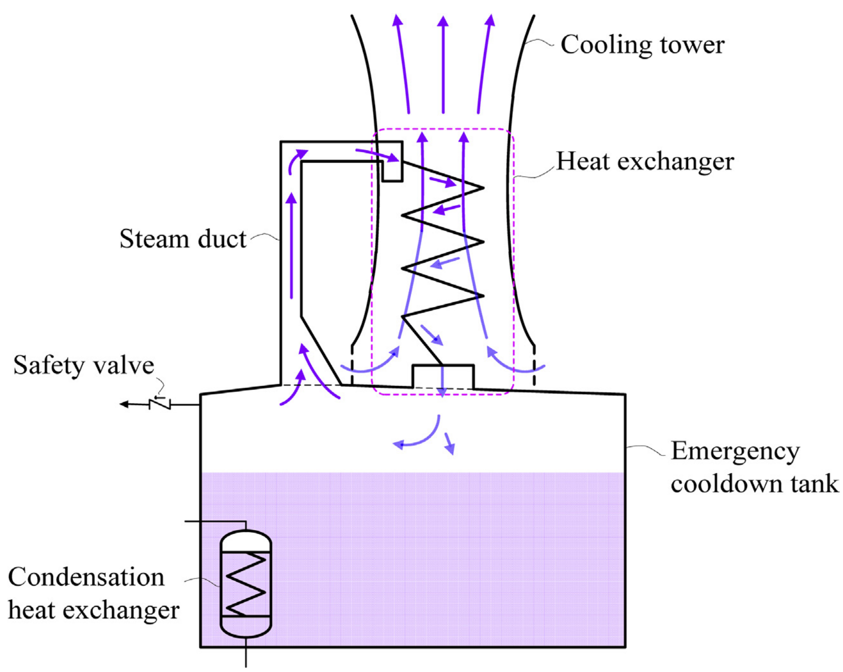

Fig. 1. Schematic of long-term passive cooling system of emergency cooldown tank (Kim et al., 2013).

predict the transition time under various conditions. A number of works have studied the transient performance of heat exchangers, but in these works, the phase of the working fluid was limited to single-phase flow, which is not applicable to air-cooled condensing heat exchangers. Moreover, many studies on natural convective heat transfer for vertical and horizontal cylinders have been reported. However, studies on transient natural convective heat transfer for an air-cooled condensing heat exchanger are rare.

In the present study, the transient performance of an air-cooled condensing heat exchanger in a long-term passive cooling system was experimentally evaluated under a decay heat load in a 1/2500-volume scaled-down model of the ECT of SMART. The corresponding cooling capacity of a vertical-type air-cooled condensing heat exchanger was calculated in order to meet the scaled design requirement of cooling capacity under a decay heat load. Moreover, the water level in the ECT was verified to be maintained continuously for longer than 72 h through the collection of steam in the air-cooled condensing heat exchanger under a decay heat load.

2. Experiments

2.1. Experimental setup

The schematic diagram of the experimental setup is shown in Fig. 2, which is a 1/2500-volume scaled-down model of the ECT of SMART. The volumetric capacity of the ECT is 0.22 m^3; it is made of SUS 304L with a 4-mm-thick plate. The diameter and height of the ECT are 600 mm and 630 mm, respectively. To reduce the flow resistance for the evaporating steam, a pipe with a 2-in (50.8 mm) outer diameter is connected between the inlet of the air-cooled condensing heat exchanger and the top of the tank. On the other hand, fully condensing flows pass through a pipe with a 1/2-in (12.7 mm) outer diameter from the outlet of the air-cooled condensing heat exchanger.

The air-cooled condensing heat exchanger, having the same design as that of Kim et al. (2015), consists of 25 1/2-in 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, and two more thermocouples were attached to the surfaces of both ends of the center tube to measure the average natural convective heat transfer coefficient of air. This experimental setup was installed in a plastic tent in which the ambient temperature could be maintained at 22 °C by an air conditioner with a cooling capacity of 3.2 kW. The air from the air conditioner was prevented from flowing directly over the tubes by using another plastic curtain.

An immersion heater (~5 kW, OMEGA VTS-3200/240) was mounted at the bottom of the tank to supply heat to water in order to simulate the condensing heat exchanger of the passive cooling system. To control the transient decay heat load, a programmable