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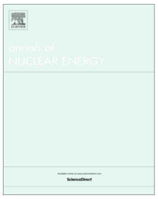

# Heat transfer in a cooling water pool with tube bundles under natural circulation

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## ABSTRACT

SMART was developed for electricity generation and seawater desalination and adopted a passive system to enhance its safety. This system could passively remove decay heat from the reactor core to the emergency cooldown tank (ECT) through the heat exchanger. A natural circulation flow was established as water covered the tube bundle inside the emergency cooldown tank. Heat transfer tests for the upward straight tube bundle in the emergency cooldown tank were performed to find the characteristics of the passive system design under natural circulation conditions. The heat transfer coefficient at the tube bundle was affected by the cooling water temperature, and the radial location of the tube. However, it has nearly a similar value at the bottom region regardless of the tube location. The average heat transfer coefficient for the tube bundle was slightly higher than that for the single tube owing to the turbulence effect among the tube bundles.

## 1. Introduction

Fresh water is continually being demanded to cope with rapid industrial growth and world population increase. However, the potential for a water decrease is real owing to the exhaustion of water resources and the spread of water pollution by industrial wastes. To resolve this problem, several kinds of energy sources including nuclear energy have been applied to seawater desalination in order to resolve the water shortage problem. SMART (System-integrated Modular Advanced Reactor), which is a 330 MWt advanced integral type PWR (Pressurized Water Reactor), was developed by KAERI (Korea Atomic Energy Institute) for electricity generation and seawater desalination. To enhance its safety, SMART adopts a passive system using gravity force as an ultimate heat sink.

This passive system, which is called a passive residual heat removal system (PRHRS), can remove decay heat passively from the reactor pressure vessel to the emergency cooldown tank through the heat exchanger (Hx) as shown in Fig. 1. The PRHRS consists of a steam generator, a heat exchanger, an emergency cooldown tank, isolation valves, and pipes (Chung et al., 2013). In the case of an event or a postulated accident in SMART, the feedwater isolation valve (FIV) and the main steam isolation valve (MSIV) are closed, and the PRHRS isolation valve is opened by a passive residual heat removal actuation signal (PRHRAS). Then, a closed loop is established with natural circulation and the heat generated in the core can be transferred to the passive residual heat removal system through the steam generator (SG). The steam generated at the steam generator secondary side is condensed at the condensate heat exchanger, and the subcooled water is returned to the steam generator by gravity force.

The condensate heat exchanger submerged in the emergency cooldown tank is located high enough above the steam generator to remove the heat transferred from the secondary system by natural circulation. The heat coming from the steam generator is transferred to the cooling water in the emergency cooldown tank through the heat exchanger. Hot water, which is transferred from the heat exchanger, is located at a low part of the emergency cooldown tank and relatively cold water is located at a high position. Then, the cooling water is circulated around the condensate heat exchanger in the emergency cooldown tank by gravity. Table 1 shows a design parameter for tube bundles for the condensate heat exchanger design. It is important to confirm a heat removal capacity at the condensate heat exchanger with tube bundles in the emergency cooldown tank which is an ultimate heat sink. Its overall capacity was confirmed to satisfy its requirement condition (Lee and Kim, 2011).

A convective heat transfer for tube bundle geometry under natural convection and natural circulation conditions is important for many engineering applications. An example of such applications includes a heat transfer at a heat exchanger and a

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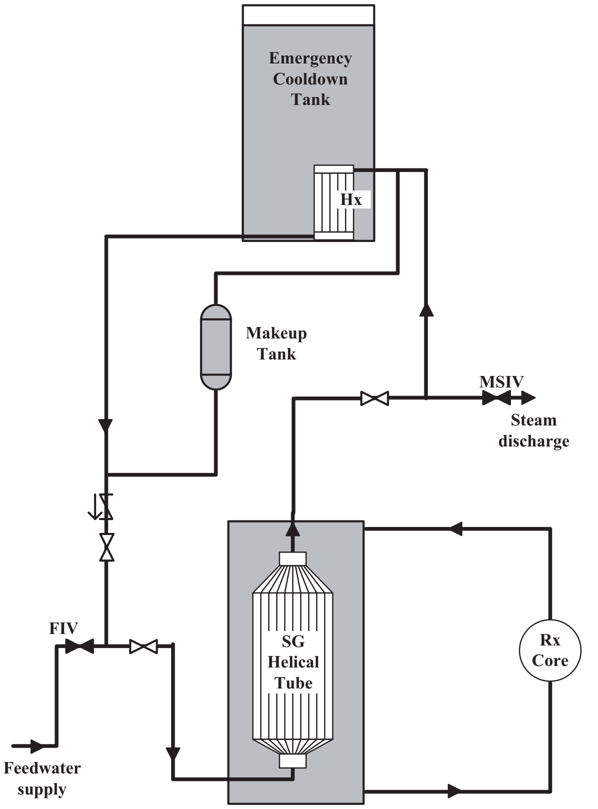

**Fig. 1.** Schematic diagram of the SMART passive residual heat removal system.

**Table 1**
Design parameters for condensate heat exchanger.

| Parameter | Value |
|---|---|
| PRHRS design pressure | 17 MPa |
| No. of PRHRS train | 4 |
| No. of tubes per train | 300 |
| Tube OD/Height | 21.3 mm/1500 mm |
| Tube pitch | 32.54 mm |
| Tube material | Inconel 600 |
| ECT operating pressure | 0.1 MPa |
| ECT water volume | 183 $m^3$ |
| ECT water temperature | Atmosphere temp. |

steam generator, and a decay heat removal from a spent fuel storage tank in nuclear power plants (Kim and El-Genk, 1989; Kang, 1998). Studies on nucleate and transition boiling heat transfer under pool and external flow conditions were reviewed (Dhir, 1991). An overview of the boiling process was presented in this paper. Similar reviews have appeared in the literature by Kenning (1977) and Fujita (1989). In addition, a heat transfer in a bundle is essential to the design and operation of open-pool type research reactors, such as the HANARO research reactor (KAERI, 1996). Numerous studies of heat transfer between a heated tube bundle and a single phase fluid have been widely investigated (Gupta et al., 2010). An experimental investigation has been carried out to determine the heat transfer coefficient during pool boiling of water over a bundle of vertical stainless steel heated tubes. Pool boiling heat transfer on the tube surface in an inclined annulus was carried out when submerged in a pool of saturated water at atmospheric pressure (Kang, 2010). The effects of the inclination angle on heat transfer were observed in the annulus with open bottoms. The main cause was considered to be the difference in the intensity of liquid agitation and bubble coalescence owing to the enclosure by the outer tube. One of the important factors in the annulus with open bottom was the convective fluid flow. Experimental studies were conducted for two-phase cross-flow conditions in horizontal tube bundles at various mass fluxes and local flow qualities (Hwang and Yao, 1986). The difference between the heat transfer performance for a heated tube in an infinite pool and in a heated or non-heated bundle was explained in terms of the different flow field geometry and thermal environment. Heat transfer coefficients were reported for the length of a horizontal shell and tube heat exchanger (Jenkins et al., 1991). The heat transfer coefficients increased from the inlet to center of the bundle. This increase could be rationalized as being due to increased turbulence including the persistence and build-up of vortices. These researches are still ongoing. However limited reaches are available in terms of natural convection, natural circulation, or combined convective heat transfer in a cooling water pool. A series of fundamental tests under natural circulation conditions have been carried out in this study to identify a bundle effect and a performance related with the tube bundle of the heat exchanger under SMART design and transient conditions.

## 2. Experimental facility

An overview of the cooling water pool and the tube bundle arrangement in the test section is shown in Fig. 2. The main components of the facility were a polycarbonate pipe enclosing the 7 heaters and a cooling water pool which corresponds to the emergency cooldown tank for the SMART design. The test-pipe was a polycarbonate tube of 1600 mm height with a 115 mm inner diameter and 2 mm thickness which can be used to observe the boiling phenomenon. The test section in the cooling water pool consisted of a bundle of stainless steel tubes for the heater. The material was SUS 316L and its outer diameter was 21.3 mm and the height was 1500 mm as shown in Table 2. The arrangement of the tube bundle is shown in Fig. 2(b) and all heaters in the bundle are surrounded by the polycarbonate tube. The tube bundle consists of seven vertical tubes having a $P/D$ of 1.53. All tubes of the bundle are connected in series and are heated electrically and the maximum power supplied was 10 kW for each heater. The current through the bundle was controlled using a variable voltage transformer. The central and peripheral tubes of the bundle were instrumented with 15 K-type thermocouples at different heights. The bulk fluid temperature was measured using 6 K-type thermocouples, placed between the tube bundle and near the test-vessel wall vertically with an equal spacing of 250 mm. All thermocouples are calibrated prior to installation at the test facility. The thermocouples were connected to a data acquisition system to record the temperature with an accuracy of ±0.2 °C. The data were acquired for heat power of 4–10 kW for each tube. The operating pressure and temperature were atmospheric pressure and 30 °C, 50 °C, and 70 °C of the cooling water temperature, respectively. The measuring variables were an outer wall surface temperature of the tube, a fluid bulk temperature at the inlet and outlet, fluid temperature among the tube bundles, and a heater power. Uncertainty of the heat transfer coefficient at the performed experiment was estimated to be less than 25%.

The cooling water maintained a constant temperature by an auxiliary heater and cooler after the pool was filled with distilled water. The tube bundle was electrically heated by the desired constant heat power. The heated water flowed in an upward direction along the test section owing to a difference in density between the polycarbonate tube and the cooling water pool, and cold fluid entering the bottom of the polycarbonate tube. An overall flow