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Parametric analysis of heat transfer rate of passive residual heat removal heat exchanger submerged in water tank

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ABSTRACT

The heat transfer performance of a miniaturized passive residual heat removal heat exchanger (PRHR HX) is experimentally investigated. It comprises 42 C-shaped tubes, submerged in a water tank that has a height of 6 m. The average heat flux is measured for various values of the working pressure and mass flow rate of the water inside the tubes. The pressure varies from 5 MPa to 15 MPa, the mass flux varies from 95 kg/(m^2 s) to 320 kg/(m^2 s), and the inlet temperature varies up to 300 °C. Moreover, the distribution of the heat flux along the tube is analyzed using empirical correlations available in the literature. The predicted heat removal rate of the tubes is in a good agreement with the measured value; the discrepancy is smaller than 4%. These results could be employed for designing PRHR HXs for nuclear reactors.

1. Introduction

The passive residual heat removal system (PRHRS) is a natural circulation loop without safety-related pumps. It can remove core residual heat even for station blackout (SBO) accidents. Therefore, PRHRS is used in advanced nuclear power plants (e.g. AP1000 and CAP1400) to improve the safety and reduce the actions required by the operator in the unlikely events of an accident [1–3]. For the advanced nuclear power plant AP 1000 and CAP1400, the C-shaped passive residual heat removal heat exchanger (PRHR HX) submerged in an in-containment refueling water storage tank (IRWST) is a critical component of the PRHRS (Fig. 1 [1]). During an SBO accident, the core decay heat is fully transferred from the PRHR HX to the IRWST. The heat transfer ability and reliable operation of the PRHR HX are very important for the reactor safety.

When the PRHR HX is actuated in an accident, the heat transfer modes at the outer surface of the PRHR HX are natural convection and subcooled boiling at the initial operation stage. The fluid in the IRWST upper region will reach a saturated value of its temperature during the heat removal process. The PRHR HX secondary side heat transfer mechanism changes from natural convection to nucleate and pool boiling. This means that the heat transfer mode at the outer surface varies for different regions of the PRHR HX. In addition, the inlet parameters (such as the mass flux, water temperature inside the tubes, and pressure) of the PRHR HX are variable during the entire process. These factors lead to a variation of the average heat flux and local heat flux distribution of the PRHR HX. Heat flux is one of the important parameters to evaluate the heat transfer performance of a PRHR HX. Therefore, it is necessary to study PRHR HXs in order to obtain local heat transfer characteristics and reveal the effect of different inlet parameters on the heat flux of the PRHR HX.

Yonomoto et al. [4] performed several tests to simulate small-break loss-of-coolant accidents in reactors using the ROSA-V large-scale test facility. PRHR HX heat transfer performances at various times were analyzed by applying several heat transfer correlations available in the literature. In their study, the Jens-Lottes correlation was chosen to calculate the nucleate boiling heat transfer coefficient at the outer surface of the tube. Both Langmuir and Churchill–Chu correlations were used to predict the natural convection heat transfer coefficient at the outer surface of the tube for the horizontal and vertical section of the PRHR HX. The fluid temperature in the tube can be, in general, predicted accurately. Jeon et al. [5] investigated the nucleate boiling heat transfer using a horizontal U-shaped heat exchanger submerged in a water pool. They assessed 15 nucleate boiling correlations using the MARS code. Then, they proposed a prediction method, and developed a nucleate boiling model. The heat transfer coefficients for the outer surface of the horizontal U-shaped heat exchanger were predicted with a good accuracy by their model. The mean deviation was 8.1%. Zhang et al. tested the pool boiling heat transfer performance of a C-shaped bundle heated by the Joule effect. It was placed in a tank that has dimensions of 3.75 m × 1.5 m × 2.2 m [6]. The main boiling heat transfer mechanisms for both vertical and horizontal bundle sections

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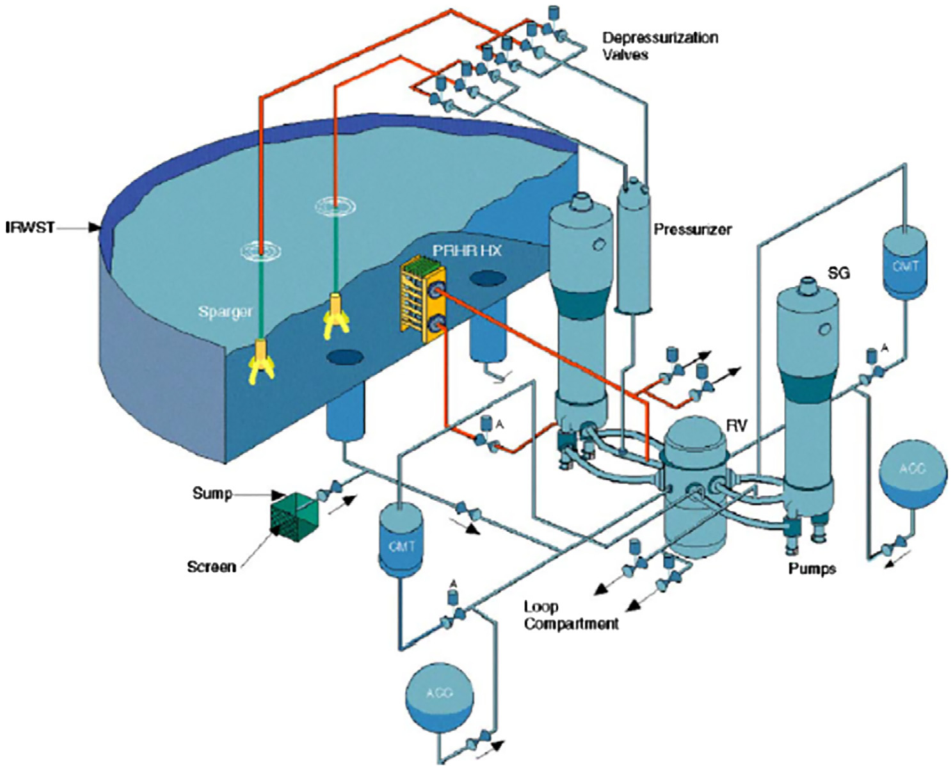

Fig. 1. AP1000 reactor coolant system and passive core cooling system [1].

were investigated and the correlations for specifically-designed C-shape PRHR HX bundle were compared with other correlations in order to assess their applicability. For the vertical bundle section, they obtained that the heat transfer coefficient (HTC) increased with the heat flux and H/D ratios. For the lower horizontal bundle section, they concluded that the typical bundle pool boiling was dominant. The Rohsenow pool boiling correlation provided a good prediction of the average HTCs. However, the heat flux along the PRHR HX tubes was uniform in their experiments; this result was different from the actual situation. Men et al. [7] studied the natural convection heat transfer performance of a C-shaped tube submerged in a tank that has dimensions of 0.6 m × 0.6 m × 1.5 m. According to the experimental data, they obtained that the McAdams correlations provided a closer fit and more reasonable trend than those of other correlations employed for calculations of the tube outside heat transfer. In their experiments, the length of the single tube was approximately 1 m. This simplification contributed to the relatively small Grashof number in the tank, which may affect the applicability of their results. Moreover, the computational fluid dynamics (CFD) was used to simulate the PRHR HX heat transfer process. Therefore, the detailed flow structure and local heat transfer characteristics were revealed. Xue et al. [8,9] used the commercial CFD software FLUENT to simulate the temperature-field and flow-field of an AP1000 PRHR HX. They investigated its heat-transfer and flow characteristics. They obtained that the flow in the IRWST was relatively complex. The region near the pipe bundle generated a strong turbulence. In addition, at some regions in the water tank a circumferential flow phenomenon emerged, which caused a number of whirlpools. Lu et al. [10] employed different Reynolds average Navier-Stokes (RANS) turbulence models and large eddy simulations (LESs) to simulate the transient heat transfer characteristics of a C-shaped rod bundle; the numerical simulations results were compared with the experimental data. They showed that all of the selected turbulence models could well describe the key changing trends of the temperature and velocity in the water tank. According to the numerical and experimental investigations, they concluded that the velocity field was generated by the temperature field, and in turn, the velocity field affected the temperature distribution. Trojan et al. [11,12] developed finite-difference based mathematical models to simulate the steady-state operation of heat exchangers with complex flow arrangements. Their models took account of the presence of scale deposits on the tube inner surface, as well as the fouling of the tube outer surface. The developed modeling technique can especially be used for modeling tube heat exchangers when detailed information on the tube wall temperature distribution is needed.

Even though the PRHR HX attracts an increasing world-wide research attention, the number of experiments focused on the specific heat transfer characteristics of the PRHR HX is still relatively small and, in addition, the number of tubes of their PRHR HX model is not very large. Therefore, experimental heat transfer data for a large-scale model are scarcely available. In this study, tests were performed on a 6 × 7 PRHR HX bundle in a tank that has a height of 6 m in order to explore the PRHR HX heat transfer characteristics for different inlet parameters. The specific heat transfer performances at different PRHR HX regions were analyzed using reported heat transfer correlations.

2. Facility and experimental methods

2.1. Test loop

PRHR HX test facility was built at the Shanghai Jiao Tong University. The schematic of the test facility is shown in Fig. 2. It comprises a main loop, cooling loop, purification loop, and instrumentation and control system. In the main loop, the distilled and de-ionized water stored in the water tank is driven by the plunger pump that operates at a pressure up to 16 MPa. The main flow goes through the regenerator to absorb the heat of the hot fluid coming from the test section. In the pre-heater, the water is heated by the Joule effect, to the required temperature. Then, it moves into the PRHR HX where it is cooled by the water in the IRWST. It exits the PRHR HX and moves towards the hot side of the regenerator and mixer. Another flow is led

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