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CHF correlation development under ERVC conditions by using the local liquid velocity from PIV measurements

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ABSTRACT

In-vessel retention through external reactor vessel cooling (IVR-ERVC) is a severe accident management strategy that removes the decay heat from the molten corium in the reactor vessel by flooding the reactor cavity. In ERVC conditions, the critical heat flux (CHF) on the outer wall of the vessel is a crucial factor that indicates a thermal margin of the system. Previous studies used averaged mass flux to predict CHF (Haramura and Katto, 1983; Lee and Mudawwar, 1988, Katto, 1990; Jeong et al., 2005; Park et al., 2013). The averaged value cannot indicate the degree of liquid supply which is the most critical factor in the CHF model. Local liquid velocity near the heated surface is one of the most crucial factors that should be quantified to develop a CHF model. In this study, the local liquid velocity near the surface has been measured. A curved rectangular flow channel was devised to simulate the gap between the external reactor vessel wall and the insulation. The boiling heat transfer and CHF were simulated with air injection at the inner wall of the test section. In the experiment, the flow field under the simulated ERVC conditions was measured using the particle image velocimetry (PIV) technique. The PIV measurement was validated by comparing the measured velocity data and the analytic solution under circular pipe flow. The liquid velocity profile at the middle plane of the curved rectangular test section was obtained in the multiple mass flux and inclination angle conditions. Based on the velocity data, a local velocity correlation was developed. The local velocity correlation was applied to improve the CHF prediction model.

1. Introduction

The importance of severe accident management in a nuclear system has increased recently. In-vessel retention (IVR) is a severe accident mitigation strategy that prevents the molten corium from leaking outside of the reactor vessel. The external reactor vessel cooling (ERVC) method has been adopted in light water reactors (LWRs) based on the IVR strategy. For example, in the APR1400 reactor, a reactor vessel is submerged into the coolant by a cavity flooding system (CFS), and the heat from the reactor vessel is removed by the mechanism of the boiling heat transfer at the external reactor wall [6].

The boiling mechanism at the downward facing surface under the ERVC conditions is different from the general pool boiling conditions. During the heat removal process, the buoyancy force induced by the density difference between liquid and vapor generates natural circulation flow in the gap between the external wall and the insulation. It makes the flow boiling condition. At the same time, the curved heat transfer area faces from downward direction to vertical. Therefor the flow conditions and the angular position have a critical effect on the boiling mechanism under ERVC conditions. Since the heat transfer mechanism is the nucleate boiling, the critical heat flux (CHF) at the reactor vessel lower head under the flow boiling condition is the success criteria for the ERVC strategy.

Much experimental research on the CHF at the reactor vessel lower head has been conducted. Theofanous et al. performed a series of ULPU experiments to obtain CHF data for the downward facing hemispheric test section which simulates AP600 and AP1000 [7,8]. The test section was a two-dimensional plate that was thick enough to simulate the real reactor condition. The natural circulation flow was developed by having a riser and a downcomer. From the ULPU test, a CHF correlation of very simple form as a function of inclination angle was suggested.

Jeong et al. conducted a CHF experiment using a two-dimensional test section that simulates the IVR-ERVC conditions in APR1400 [4]. The test section was designed to have maximum

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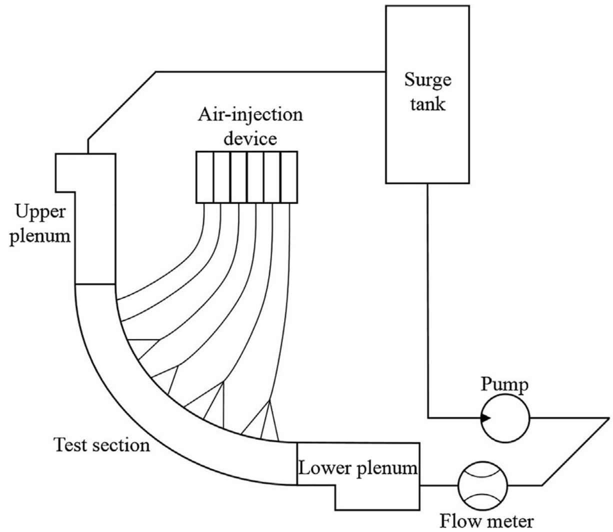

Fig. 2-1. Schematic of the flow loop.

heat flux at a 90° inclination angle from the bottom to simulate a gradual increase of heat flux on the external wall of the reactor vessel. The radius of the test section was 2.5 m, which matched the real scale of the reactor vessel. The CHF was measured under various mass flux conditions from 0 to 300 kg/m^2 s, and the two-phase flow near the heated surface was visualized through a transparent window. Based on the experimental data, a CHF correlation was proposed as a function of mass flux and exit quality.

Park et al. performed a CHF experiment with test sections of various radii and gap sizes [5]. The flow channel was rectangular, and two-dimensional test sections were utilized to simulate the outer wall of the reactor vessel. The radii of the test sections were 150, 250, and 500 mm, and the mass flux conditions ranged from 100 to 400 kg/m^2 s [9]. Two-phase boundary layer flow was visually observed in the flow channel. From the experimental data, a CHF correlation was suggested regarding the mass flux and the modified exit quality.

The CHF prediction correlations proposed in the previous research were developed based on the averaged parameters such as mass flux and thermodynamic steam quality [1–5]. However, the CHF phenomenon is profoundly affected by local parameters. Thus, the CHF model needs to be based on the local conditions. The local liquid velocity near the heated surface is one of the local parameters that needs to be studied to explain the mechanism of the CHF under ERVC conditions.

In this study, an air-water flow loop was devised to simulate the flow near the reactor vessel external wall under the ERVC condition. The liquid velocity of the flow was measured via the particle image velocimetry (PIV) technique. Based on the local liquid velocity measurement results, the local velocity correlation was developed. The local liquid velocity was used to develop a CHF correlation for ERVC conditions.

2. Experiments

An experimental facility was set up to measure the local velocity under ERVC conditions. The facility consisted of two parts: a flow loop and a PIV measurement system. The flow loop was designed to simulate the CHF occurring in the ERVC situation. The PIV system was installed to measure the liquid velocity of the flow in the test section.

2.1. Air-water flow loop and test section

The flow loop was made according to the test section of Park et al. [5]. As depicted in Fig. 2-1, the loop consisted of a test section,

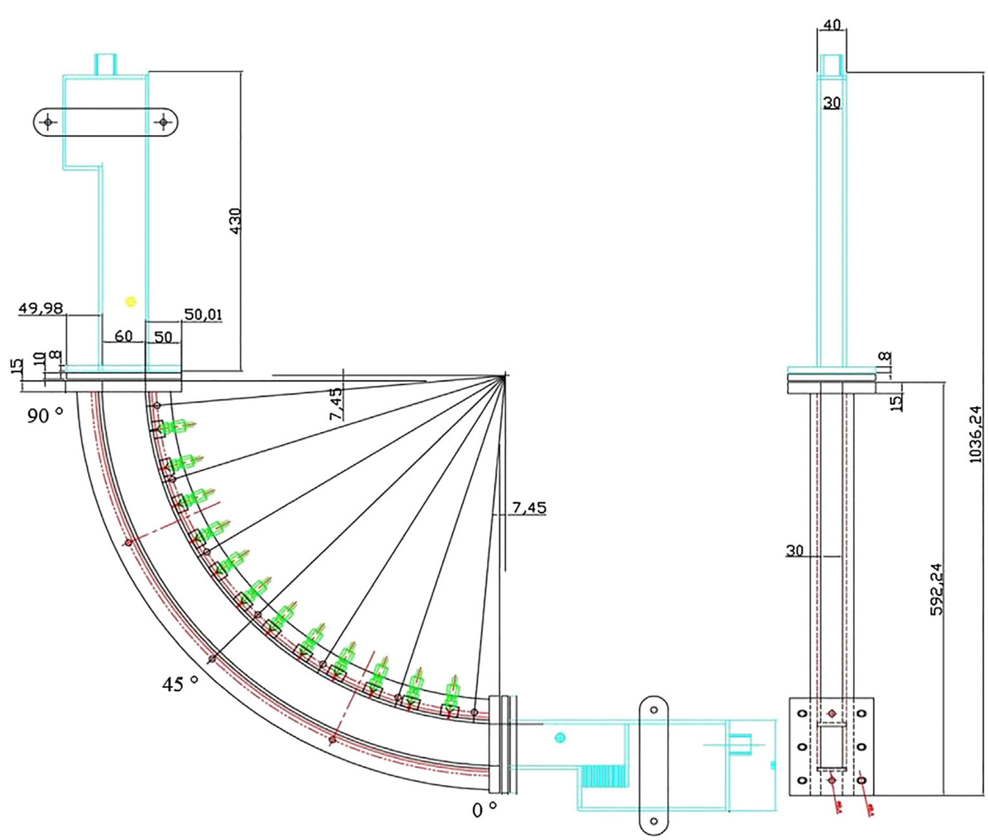

Fig. 2-2. The front and the side view of the test section.