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Experimental study of critical heat flux enhancement with hypervapotron structure under natural circulation conditions

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HIGHLIGHTS

- Natural circulation tests are performed to study the effect of hypervapotron on CHF.
- Hypervapotron structure improves CHF under natural circulation conditions.
- Visualization data illustrate vapor blanket behavior under subcooled flow conditions.

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ABSTRACT

The enhancement of critical heat flux with a hypervapotron structure under natural circulation conditions is investigated in this study. Subcooled flow boiling CHF experiments are performed using smooth and hypervapotron surfaces at different inclination angles under natural circulation conditions. The experimental facility, TESEC (Test of External Vessel Surface with Enhanced Cooling), is designed to conduct CHF experiments in a 30 mm by 61 mm rectangular flow channel with a 200 mm long heated surface along the flow direction. The two-phase flow of subcooled flow boiling on both smooth and hypervapotron heating plates is observed and analyzed by the high-speed visualization technology. The results show that both smooth surface and hypervapotron surface CHF data exhibit a similar trend against inclination angles compared with the CHF results under forced flow condition on the same facility in earlier studies. However, the CHF enhancement of the hypervapotron structure is evidently more significant than the one under forced flow conditions. The experiments also indicate that the natural flow rates are higher with hypervapotron structure. The initiation of CHF is analyzed under transient subcooling and flow rate conditions for both smooth and hypervapotron heating surfaces. An explanation is given for the significant enhancement effect caused by the hypervapotron surface under natural circulation conditions. The visualization data are exhibited to demonstrate the behavior of the vapor blanket at various inclination angles and on different surfaces. The geometric data of the vapor blanket are quantified by an image post-processing method. It is found that the thickness of the vapor blanket increases with the increase of the inclination angle. Surface wettability and roughness are measured for both smooth and hypervapotron surfaces before and after the CHF experiments.

1. Introduction

In-vessel retention (IVR) through external reactor vessel cooling (ERVC) is an important severe accident management strategy (SAMS) adopted by many light water reactors (LWRs) like AP600, AP1000, APR1400 and CAP1400. During a postulated severe accident, a large amount of molten fuel and other core structural material would be relocated to the lower head of the reactor pressure vessel (RPV). In order to remove the decay heat generated from the molten corium, ERVC strategy utilizes water to cover the external surface of the reactor lower head. Nucleate boiling on the vessel outer surface could remove the decay heat conducted through the vessel wall. As long as the heat flux from the molten core does not exceed the critical heat flux (CHF) for the nucleate boiling on the outer surface of the RPV lower head, the reactor vessel could be sufficiently cooled and the vessel failure would be prevented.

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In the past two decades, IVR-ERVC strategy has been widely investigated on several different experiment facilities. In the late 1990's, Chu et al. (1997a,b) conducted a series of full-scale quenching experiments to simulate the downward-facing boiling process on the outer surface of an RPV lower head using the CYBL (Cylindrical Boiling) facility at Sandia National Laboratories. The critical heat flux they found was approximately equal to 50 W cm^{-2}. SULTAN experiment (Rouge, 1997) was a series of one-dimensional experiments to study the large-scale structure coolability by water in boiling natural convection. The experiments investigated the effect of different parameters on CHF and concluded that heat fluxes larger than 1 MW m^{-2} would be removed under natural water circulation conditions. ULPU experiment was a full-scale downward-facing two-dimensional experiment that applied IVR to AP600 (configurations I II and III) (Theofanous et al., 1996) and AP1000 (configurations IV and V) (Theofanous et al., 2002; Dinh et al., 2003). Cheung et al. (1997) utilized SBLB (Subscale Boundary Layer Boiling) facility to perform a subscale three-dimensional simulation for the downward-facing boiling process. Transient quenching and steady state boiling experiments were performed under both saturated and subcooled conditions and a complete database on CHF was obtained. CASA (Corium Ablation Stopper Apparatus) (Noh and Suh, 2013) was a scale down downward-facing hemispherical test facility for APR1400 with an asymmetric thermal insulator and sixty-one in-core instrumentation (ICI) tubes and four shear keys.

With a trend of increased power level of larger PWRs, IVR-ERVC research started to focus on the designs and techniques that can enhance CHF performance under severe accident conditions. In addition, in the post-Fukushima era, the uncertainty of the configuration of corium also called for more safety margin against the critical heat flux during the entire severe accident transient. Yang et al. (2005) investigated the effect of surface coating on the critical heat flux for downward facing boiling on the SBLB facility. At all angular locations explored in their experiments, appreciably local CHF value enhancement was demonstrated by applying a microporous coating onto the heating surface. Researchers from MIT (Massachusetts Institute of Technology) summarized the CHF enhancement studies by nanofluids and found that large effects on CHF (up to +200%) could be obtained at relatively low nanoparticle concentrations (as low as 0.001%vol) (Bang et al., 2008). They also investigated the feasibility of applying nanofluids to enhance CHF under IVR conditions (Buongiorno et al., 2009). Kim et al. (2012) conducted CHF experiments using a 2-D curved test section with TSP (Trisodium Phosphate) and BA (Boric Acid). Results showed that CHF could be enhanced by as much as 50% with TSP solution, BA solution, and TSP+ BA solution except for the condition of 150 mm radius with BA solution. Yang et al. (2016) utilized chemical solution with the addition of BA and TSP to investigate the CHF characteristics of chemical solution boiling on a downward facing curved real reactor pressure vessel material surface (SA508III steel). Results showed that CHF values exhibited different changes in different chemical solution environment for the SA508III steel material. Sohag et al. (2017) applied a new and versatile micro-porous coating technique called "Cold Spray" to investigate the critical heat flux enhancement by micro-porous coating. 90% enhancement was reportedly achieved using the Cold Spray coated vessel in their quenching boiling experiments.

The enhancing techniques mentioned above mainly focus on the modification of micro-structure of the heating surface toward CHF enhancing properties. Hypervapotron, a single-sided heating surface with fins, which was chosen as one of the secondary sides of the divertor plate for ITER (International Thermonuclear Experimental Reactor), shows promising CHF enhancement under ERVC conditions. Experiments conducted by Boscary et al. (1998) indicated that significant CHF enhancement could be achieved by a hypervapotron compared with a smooth tube with two cooling channels at a high axial velocity of 10 m s^{-1}. Chen et al. (2008a, b) conducted hypervapotron experiments at low subcooled conditions using R134a and found hypervapotron could enhance CHF for approximate 50% compared with the smooth surface. Wang et al. (2014) observed and measured the multiphase flow and heat transfer phenomena quantitatively on the surface of grooves and triangular fins hypervapotron structure with the help of several measurement techniques. Lin and Chen (2012) investigated the subcooled flow boiling using R-134a at the low-pressure range on plain and hypervapotron surfaces and found a 40–50% higher CHF under same thermo-hydraulic conditions. They also proposed an improved hot spot model to predict CHF for flat and hypervapotron heating surface in subcooled flow nucleate boiling (Lin et al., 2015). A more recent report was attempting to demonstrate the potential of hypervapotron structure in IVR application (Zhao et al., 2016). The paper showed that hypervapotron improved CHF performance by 40–60% compared with the smooth surface under forced flow conditions.

Advanced LWRs, such as AP600 and AP1000, adopt passive safety system in IVR-ERVC design and CHF data obtained under forced flow conditions may be non-prototypic. Under natural-circulation conditions, boiling systems can show various flow oscillations and previous studies have shown that flow oscillations can induce a premature CHF at the heat flux level much lower than that for stable conditions (Mishima et al., 1985). The two-phase flow and CHF characteristics under natural circulation conditions may vary substantially from those under forced flow conditions. Thus, this report is to extend the investigation of the CHF enhancement of hypervapotron into natural circulation, a more prototypic IVR-ERVC condition.

2. Experimental method

The subcooled flow CHF experiments were conducted on the TESEC (Test of External Vessel Surface with Enhanced Cooling) facility. Fig. 1 illustrates the schematic of TESEC design. A detailed discussion of TESEC was reported in the early paper (Zhao et al., 2016), and only a brief overview of the experiment is presented in this paper.

2.1. Test loop

The configuration of the test loop is redesigned for the natural circulation experiments. The major components of the test loop system include a test section, a flow meter and an upper tank with an auxiliary cooling unit. This experiment uses deionized (DI) water as the working fluid. The pre-heater in the pre-heating loop is utilized to set the initial temperature conditions in the upper tank in the preparation part of the experiments. When the fluid temperature in the upper tank reaches the desired value, which is 95 °C in this study, the working fluid will be switched to the test loop. The auxiliary cooling unit in the upper tank removes the heat from the returning water and maintains the temperature in the upper tank to be 95 °C.

2.2. Test section

The test section consists of a 30 mm by 61 mm rectangular flow channel and a heating module. The entire test section is mounted on a rotating arm and it can be fixed at ten different inclination angles from 0° (horizontal) to 90° (vertical). Fig. 2 depicts the configuration of the heating module. The heating module includes a copper heater block heated by cartridge heaters and a heating plate. A separate heating plate made of 99.9% copper is installed