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An experimental study of hypervapotron structure in external reactor vessel cooling

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HIGHLIGHTS

- Experiments are performed to study the application of hypervapotron in ERVC design.
- CHF experiments on two surfaces are conducted under different flow conditions.
- Hypervapotron improves CHF performance by 40–60% compared with smooth surface.
- Visualization shows fin structure removes vapor mushroom for better liquid supply.

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ABSTRACT

In vessel retention (IVR) is one of the key strategies for many advanced LWR designs to mitigate postulated severe accidents. The success of IVR substantially relies on external reactor vessel cooling (ERVC) by which the decay heat is removed from the melt core in the reactor vessel lower head. The main challenge of IVR is to provide an adequate safety margin of ERVC against critical heat flux (CHF) of subcooled flow boiling in the reactor lower head flow channel. Due to uncertainties in corium melt pool configuration, large CHF margin of ERVC is usually required by regulatory authorities to demonstrate reliability of severe accident mitigation methods. Various CHF enhancement designs have been proposed and studied in literature. In this paper, an experimental study of hypervapotron structure as a novel design to improve CHF performance of ERVC is conducted. Hypervapotron is chosen as one of the potential engineering options for International Thermonuclear Experimental Reactor (ITER) program as a divertor structure to remove highly intense heat from fusion chamber. This study is to conduct CHF experiments at typical PWR ERVC working conditions. The CHF experiments are performed in a 30 mm by 61 mm rectangular flow channel with a 200 mm long heated surface along the flow direction. Both smooth and hypervapotron surface are tested at various inclination angles of the test section to simulate various positions of the reactor lower head. The hypervapotron is found to have a 40–60% CHF improvement compared with the smooth surface. The high speed visualization indicates that hypervapotron is able to effectively remove big vapor mushrooms on the heating surface.

1. Introduction

In vessel retention (IVR) is one of the key severe accident mitigation strategies for numerous advanced pressurized water reactor (PWR) designs, such as AP600, AP1000, APR1400 and CAP1400. IVR designs utilize the reactor pressure vessel lower head to contain molten fuel and rely on external reactor vessel cooling (ERVC) to remove decay heat. After the reactor pressure vessel (RPV) cavity is flooded with water, the decay heat is removed by conduction through the RPV wall and flow boiling on the outer surface of the RPV. The heat transfer of flow boiling is adequately efficient to maintain the PRV material at a moderate temperature in order to provide necessary structural strength to support the pressure vessel and molten fuel. However, the capacity of ERVC is limited by the critical heat flux (CHF) of flow boiling on the outside of the reactor vessel surface. In addition, the configuration of corium may result in adverse heat flux distribution along the reactor lower head which further increases the possibility of thermal failure due to the occurrence of CHF at high heat flux regions. Reactor vendors need to demonstrate that ERVC design has reasonable safety margin against

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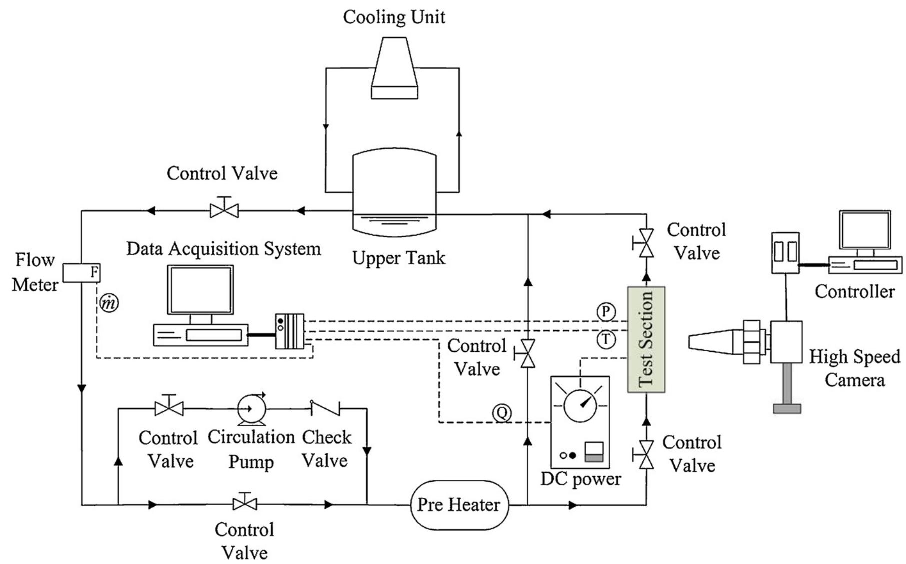

Fig. 1. Schematic diagram of TESEC facility.

CHF at the reactor lower head during the entire severe accident transient.

Theofanous et al. (1996) carried out a comprehensive work to apply IVR strategy to the first passive PWR plant AP600. They conducted a two-dimensional slice, full height experiment (ULPU-III) to obtain CHF values for AP600 configuration and successfully demonstrated ERVC design has enough safety margin against the thermal load from the corium in the reactor lower head. Following the pioneering work done by Theofanous, it has been an active research interest to understand the CHF characteristics of downward facing spherical heating surface and hunt for novel methods to enhance CHF performance that may allow adoption of IVR strategy in higher power level PWRs.

Dinh et al. (2003) conducted ULPU-V experiments with improved flow channel and obtained higher CHF values compared with ULPU-III to support the AP1000 IVR design. Rempe et al. (2004) proposed a new vessel/insulation design that maximizes the bottleneck flow area to enhance CHF performance for APR1400. Jeong et al. (2005) identified the CHF limit for the IVR-ERVC strategy on the APR1400 reactor using a two-dimensional slice test section.

With early success in achieving higher CHF performance by favorable flow channel configuration, the focus of recent IVR-ERVC studies has been shifted to optimize surface conditions for further CHF enhancement. Azizian et al. (2015) investigated CHF performance of pre-oxidized surface and found a certain combination of base material and oxidization layer may have higher CHF values compared with bare material. However, Son et al. (2015) and Son et al. (2016) reported that pre-oxidization of the SA508 heater reduced the CHF performance. Seo and Bang (2015) and Seo et al. (2015) studied CHF characteristics of artificially modified heating surface prepared by various film coating techniques. Preliminary face-up pool boiling data show that carbon nanotube (CNT) films may have moderate CHF enhancement.

Hypervapotron, a single-sided heating surface with fins, was chosen as one of the secondary sides of the divertor plate for ITER. Experimental results (Raffray et al., 1999) indicated that hypervapotron is able to increase CHF by 100% at 4 MPa subcooled flow boiling condition compared with smooth tube (water as coolant). Escourbiac et al. (2003) investigated various hypervapotron designs and some of them were able to obtain more than 130% CHF enhancement at high subcooled conditions (113–127 °C, water). Chen et al. (2008a,b) conducted hypervapotron experiments at low subcooled conditions using R134a and found an approximate 50% CHF enhancement compared with the smooth surface. Early work indicates that hypervapotron has advantageous CHF performance and may be adopted in ERVC designs. This paper is to report an experimental study of hypervapotron structure at typical ERVC flow conditions to demonstrate its potential in IVR application.

2. Experiment apparatus and instrumentation

2.1. Experiment set-up

The schematic diagram of the experiment facility "Test of External Vessel Surface with Enhanced Cooling" (TESEC) is shown in Fig. 1. The TESEC test facility consists of a closed loop system and an instrumentation system. The loop system includes a test section, a circulation pump, an upper tank and an auxiliary cooling unit. The circulation of the deionized water in the loop is driven by a circulation pump with variable frequency control, and the maximum flow rate is about 7 m^3/h. The water from the test section returns to the upper tank which is cooled by the auxiliary cooling unit. A feedback circuit is installed with thermocouples in the upper tank and the auxiliary cooling unit so that the water temperature in the upper tank can be stably maintained at a desired value. The vertical distance between the upper tank and the test section is 5 m.

The test section consists of a rectangular flow channel, a pre-heating module and a primary heating module as illustrated in Fig. 2. The entire test section is mounted on a rotating arm which can be set at different inclination angles from 0° (horizontal) to 90° (vertical). The rectangular flow channel is made of stainless steel, and is 30 mm wide, 61 mm high and 200 mm long. Two quartz windows are installed at the sidewalls of the flow channel for visualization. A pre-heating module of 14 kW is installed to obtain a desired inlet temperature. Working with a thermocouple installed after the pre-heating module, the inlet temperature uncertainty of the primary heating module can be maintained within ±1 °C. The primary heating module has a total capacity of 21 kW and has three heating regions that can be controlled independently. The primary heating module can provide a maximum heat flux of 2.8 MW/m^2. A separate heating plate is installed at the bottom of the primary heating module to perform boiling heat transfer experiments for various