Annals of Nuclear Energy 113 (2018) 344–352

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Effects of downward-facing surface type and inclination on critical heat flux during pool boiling

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A R T I C L E I N F O

Article history:
Received 24 April 2017
Received in revised form 10 November 2017
Accepted 26 November 2017

Keywords:
Critical heat flux
Downward-facing pool boiling
Honeycomb surface
Inclined surface
Water supply
Bubble removal

A B S T R A C T

The effectiveness of ex-vessel cooling systems in response to severe nuclear reactor accidents is attributable, in part, to the critical heat flux (CHF). As such, CHF enhancement has been the focus of significant research. Prior studies have demonstrated that porous and specifically, honeycomb surfaces can increase the CHF. In this study, we compared the CHF of bare- and various honeycomb downward-facing surfaces during pool boiling. In addition, we investigated the effects of surface inclination on the CHF. The results indicated that the honeycomb surfaces had higher CHF values than the bare surface. The honeycomb surfaces provided separate water supply and bubble removal paths, which decreased the liquid–vapor counterflow resistance and increased the water supply to the heating surface for cooling. The porous honeycomb surfaces (with 5-, 20-, and 100-μm pores) had higher CHF values than the honeycomb surface with no pores (with 0-μm pores). Among the different porous surfaces, the CHF values were equivalent. With respect to inclination, the results indicated that the CHF increased as surface inclination increased for both bare and honeycomb surfaces. The increased surface inclination facilitated bubble removal and again increased the water supply to the heating surface for cooling. Thus, the water supply and bubble removal capacities are two underlying factors affecting the CHF. The CHF (and ultimately ex-vessel cooling system effectiveness) is determined by the limiting water supply or bubble removal capacities. In this study, the bubble removal capacity was consistently the limiting factor for determining the CHF.

1. Introduction

A nuclear reactor accident is considered severe when it involves fuel damage inside the reactor and causes a radioactive release into the reactor vessel, containment area, or broader environment. Ex-vessel cooling systems have proven effective in responding to severe accidents occurring in conventional nuclear power plants (NPPs), including the Fukushima Daiichi NPP. In these systems, the critical heat flux (CHF) in the lower head of the reactor vessel is used to assess the cooling effectiveness. Newly developed NPPs have a higher thermal power than conventional NPPs and thus require a higher cooling capacity. As such, significant attention has been recently focused on CHF enhancement.

Liter and Kaviany (2001) purported that the CHF in either pool or forced-flow boiling can be increased through surface modification. Using a bare surface for reference, select researchers found that a microfin structure had higher CHF values, and that the CHF increased as the number of fins increased (Wei and Honda, 2003; Zhong et al., 2015). The reason for CHF enhancement was that the micro-fin structure could mitigate liquid-vapor flow instabilities. Further; this type of structure ensured stable nucleation sites to maintain liquid rewetting and hinder surface dry-out. In addition, CHF was enhanced in nanoparticle solutions as an uneven coating is deposited on the test surface, which is detected using scanning electron microscopy (SEM) (Kim et al., 2007; Ahn and Kim, 2013). Using a liquid sublayer dry-out model, Choi et al. (Choi et al., 2017) investigated CHF performance through the application of nanoparticles. After nanoparticle deposition, the bubble departure diameter became larger, resulting in an increase of two parameters, namely, the liquid sublayer thickness and the passage time of vapor blanket. Finally, CHF was enhanced by the compensation of these two parameters. Other researchers have used radiation induced surface activation (RISA) to enhance CHF (Imai et al., 2002; Takamasa et al., 2009; Okamoto et al., 2002). Following RISA, droplet tests indicated that the contact angle on an irradiated surface was significantly reduced compared with that on a nonirradiated surface, which effectively modified the test surface wettability and subsequently increased the CHF.

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https://doi.org/10.1016/j.anucene.2017.11.048
0306-4549/

In an alternate approach, select researchers found that a modulated porous layer adhered to the heating surface can reduce the liquid-vapor counterflow resistance adjacent to the surface and ultimately increase the CHF by affecting the hydrodynamic and viscous-drag limits (Hwang and Kaviany, 2006). Based on porous-layer structure theory, Mori and Okuyama (Mori and Okuyama, 2009) and Mori et al. (Mori et al., 2010) introduced a novel honeycomb structure comprising ceramic particles that was found to increase the CHF 2.5 times in an upward-facing pool boiling experiment. They suggested that separate flow paths for both the bubble and water flow were a key issue for CHF enhancement. Specifically, during boiling, the water flow would penetrate through the porous honeycomb surface and approach the heat source to cool down the heating surface. Then, bubble generated by heat transfer escaped from the holes, forming two separate flow paths. This type of structure could decrease the liquid-vapor flow resistance, ensuring that a greater amount of water is used for cooling.

Wei et al. (Wei et al., 2017) investigated bubble behavior with 1/16 scaled-down, downward-facing facility used for the development of CAP1400. The results of their study indicated that several processes are involved in vapor generation, namely, (a) separation, (b) coalescence, (c) sliding, and (d) break-up. However, for a complete downward-facing direction (inclination angle ranging from 0° to 27°), the boiling was mainly characterized by the appearance of discrete bubbles and small coalescence. Moreover, they defined the occurrence of CHF performance, which is the symbol of sudden decrease in vapor bubble height and increase in boiling cycle frequency.

The aim of this study was to advance prior research efforts related to CHF enhancement and support NPP cooling system design. According to previous research, surface modification does have an effect on CHF enhancement. Thus, it is necessary to conduct tests on a honeycomb surface. However, a sufficient knowledge on honeycomb surface is not available, and there exist some deficiencies in a few surface modification methods. To begin with, prior research on honeycomb surfaces had mostly focused on upward-facing pool boiling, which is against the boiling direction (downward-facing) in an actual ex-vessel reactor cooling system. Moreover, prior honeycomb structures used were ceramic; in this study, we considered a stainless-steel honeycomb structure with increased strength. Secondly, the manufacturing technology of micro-fin structure is a slightly complex (Wei et al., 2005); thus, it is necessary to propose an easier method for future engineering applications. Considering the abovementioned factors, a honeycomb surface was selected in the present study.

In this study, we compared the CHF of bare and different honeycomb surfaces during pool boiling to test the honeycomb effect on CHF performance. More specifically, we performed a downward-facing, rather than an upward-facing, pool boiling experiment to better reflect the CHF in the lower head of the reactor vessel. Because the lower head of the reactor vessel is a spherical structure, the CHF varies along a circular arc. To reflect this phenomenon, we also investigated the effects of surface inclination on the CHF. Considering the fact that the parameters of a honeycomb surface have not been widely researched, pore size was selected in the experiment. Further, for a better understanding of the relatively different bubble behavior, we considered one small scaling facility (detailed parameters are list in the following discussion).

2. Experimental equipment and methods

The experimental equipment used in this study can be categorized into experimental equipment and data acquisition equipment. The experimental equipment included a water tank (inner size is 220(L) × 180(W) × 210(H), unit in mm) and its support, a test section, a condenser, a preheater, and a thermocouple measuring the pool water temperature. Prior to testing, the pool water was heated to saturated conditions under atmospheric pressure. During testing, the preheater was used to maintain a constant water temperature. Distilled water was used in the water tank. The data acquisition equipment included a high-speed camera positioned under the water tank to capture the boiling phenomenon and a data logger used for parameter measurement. Fig. 1 provides a schematic of this experimental equipment setup.

The test sections comprised copper (heating zone) and polyether ether ketone (PEEK, thermal isolation zone). The detailed geometrical information of the copper block is shown in Fig. 2(c). The copper boiling surface was 30 mm × 30 mm. Cartridge heaters, with a 225-W power rating per heater, provided heat from the top of the test sections. Three apertures toward the bottom of the test sections, spaced at 3-mm intervals, housed the thermocouples. The three K-type thermocouples, with a 0.75% uncertainty, were used to measure the temperature at the center of the test sections. Fig. 2 provides a schematic of the test sections for the bare and honeycomb surfaces. The test section for the honeycomb surface [Fig. 2(b)] included a 1-mm gap between the copper and PEEK materials that allowed installation of the 1-mm-thick honeycomb plate.

Fig. 3 depicts the test sections for the bare and honeycomb surfaces considered in this study. The boiling area of both surfaces was the same. The honeycomb surface was fabricated from sintered stainless steel with 1.7-mm hole diameters. To better understand the honeycomb structure effects, honeycomb surfaces with different pore sizes (0-, 5-, 20-, and 100-μm) were considered. Here, pore size means the diameter of the largest particles that can penetrate through honeycomb surface. Fig. 4 depicts the test sections for the various honeycomb surfaces considered in this study.

Before each experiment, two main steps, namely, preparation and degassing, need to be performed. The copper block and honeycomb surface need to be prepared. The detailed procedure for preparing the copper block is as follows (a) use P1200 sand paper to polish the copper surface; (b) use acetone to clean the copper surface; (c) use distilled water to wipe off the remaining substance. If the honeycomb surface experiment is planned to be conducted, the surface will be boiled in distilled water for several hours. Degassing is performed just before the experiment starts.

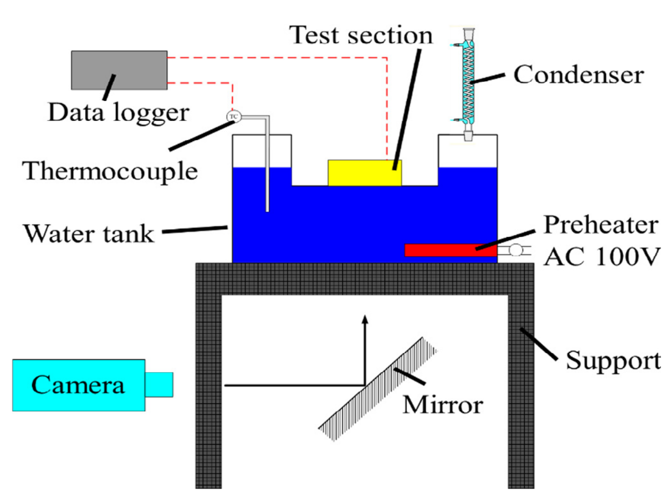

Fig. 1. Schematic of the experimental equipment setup.