Applied Thermal Engineering 134 (2018) 594–602

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Experimental study of downward facing boiling on a structured hemispherical surface

Dawen Zhong[a], Jun Sun[b], Ji'an Meng[c,*], Zhixin Li[c]

[a] School of Nuclear Science and Engineering, North China Electric Power University, Beijing 102206, PR China
[b] Key Laboratory of Advanced Reactor Engineering and Safety, Ministry of Education, Tsinghua University, Beijing 100084, PR China
[c] Key Laboratory of Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, PR China

HIGHLIGHTS

- A novel heating system with the liquid metal as the intermediate heat transfer medium is introduced.
- Boiling characteristics on downward facing surfaces are studied via experimental observation and test data.
- The effect of inclination angle on CHF were investigated.
- Compared with plain surface, at least more than 59% CHF increase could be obtained on IGTAC surface.

ARTICLE INFO

Keywords:
Downward facing boiling
Critical heat flux
Convection of liquid metal
Structured hemisphere surface

ABSTRACT

A heating system with liquid metal as the intermediate heat transfer medium was introduced into a scaled three-dimensional reactor vessel. The liquid metal was heated by heaters and then circulated inside a hemispherical vessel. Then, the outer surface of the lower head was cooled by boiling water. The objective of this study is studying the boiling regimes and heat fluxes on the outer surface of the hemispherical lower head. The boiling heat transfer was investigated on a hemispherical plain surface and on a surface with interconnected grooves with triangular cavities surface using saturated deionized water at atmospheric pressure. The critical heat flux (CHF) on the plain surface at an inclination angle of 85° was 857.3 kW/m^2, with no boiling crisis observed on the structured surface up to the highest heat flux of 1366.9 kW/m^2 at the inclination angle of 85°, with the liquid metal temperature higher than 400 °C. Thus, the CHF on the structured surface was more than 59% greater than on the plain surface at an inclination angle of 85° with the liquid metal temperature inside the pressure vessel reduced by 80–100 °C for the same heating power. The structured surface forms a liquid-vapor conversion path with the cavities as stable nucleation sites and the interconnected grooves as cooling water supply pathways. Thus, the structured surface significantly enhances the boiling heat transfer and the CHF.

1. Introduction

The Fukushima nuclear accident has attracted the attention of all researchers in the nuclear field. The Chinese government launched a major project in 2011 to investigate the phenomenology and mechanisms of serious accidents in advanced light water reactors to avoid such accidents. In-vessel retention is a key severe accident management strategy which is used in some new nuclear power plants and has been proposed for some advanced light water reactors. One method to achieve in-vessel retention is External Reactor Vessel Cooling (ERVC), which has been investigated by many researchers. During a severe accident, if the reactor core cannot be cooled sufficiently by the coolant, the core materials start to melt and fall into the lower head due to gravity. The ERVC floods the reactor cavity to submerge the reactor vessel and cool the core debris which has relocated into the vessel lower head during the severe accident [1]. To remove the heat generated by the nuclear fission through boiling heat transfer, the heat flux from the core molten debris should not exceed the CHF for boiling heat transfer on the reactor vessel outer surface. Therefore, the vessel outer surface temperature could be kept near the water saturation temperature to maintain the vessel structured integrity. The AP1000 reactor vessel outer surface is a bare surface and the ERVC system for AP1000 does not have a large safety margin. Therefore, the boiling heat transfer coefficient and CHF on the reactor vessel downward facing surface

---

* Corresponding author.
E-mail address: mja@tsinghua.edu.cn (J. Meng).

https://doi.org/10.1016/j.applthermaleng.2018.02.031
Received 14 August 2017; Received in revised form 9 January 2018; Accepted 9 February 2018

should be enhanced.

There have been many experimental and theoretical studies to investigate the effect of inclination angle on the CHF for a plain surface. Henry and Fauske [2] and Chu et al. [3,4] investigated the heat removal capabilities for external cooling of the reactor pressure vessel lower head to prevent lower head failure. Both studies indicated that the external cooling method can prevent core debris leakage from the reactor vessel. Dinh [5] and Theofanous et al. [6] conducted full-scale experimental studies of the boiling crisis phenomenon on the outer surface of a hemispherical reactor vessel using a two-dimensional copper slice with independently heated zones in the ULPU facility at UCSB. They investigated downward facing boiling heat transfer by adding a baffle as thermal insulation. Their results showed that flow path streamlining improved the in-vessel retention for higher power reactors.

Cheung and Haddad [7,8] experimentally studied downward facing boiling and the CHF on the outside surface of a hemispherical lower head 0.305 m in diameter in the subscale boundary layer boiling (SBLB) facility, which provided scaled 3D simulations of downward facing boiling with and without thermal insulation. Transient and steady state boiling experiments with both saturated and subcooled conditions were conducted to obtain a CHF database. The CHF was found to increase almost linearly from the bottom center toward the upper edge of the vessel. The CHF increased from 0.4 MW/m^2 to 0.9 MW/m^2 for $0^\circ \le \theta \le 67.5^\circ$. Two types of thermal insulation were used for both the AP600 nuclear power plant and the KNGR1300 nuclear power plant [9,10]. The CHF with thermal insulation was consistently higher than without thermal insulation.

There are several ways to enhance the ERVC performance for in-vessel retention. Various modifications of the boiling surface have been developed to enhance the boiling heat transfer coefficient and CHF for saturated pool boiling. For example, studies have considered micro-porous coatings using sintered metal powders [11–14], the cold spray method [15], nanoparticle deposition onto the surface [16], and various surface structures [17–21] such as honeycomb porous plates [17,18], pin fins [19], and micro channels [20,21].

Dizon et al. [11] and Yang et al. [12] investigated the boiling and CHF on downward facing surface with micro-porous coatings in the SBLB facility. The CHF on the micro-porous coating surface was increased to 0.849–1.880 MW/m^2. The results showed that the local CHF could be enhanced by 42–112% over a plain vessel surface using micro-porous coatings. Sohag et al. [15] developed a Cold Spray technique to coat a commercial size reactor vessel with the effects of subcooling and coating on the CHF investigated in the SBLB facility. Higher nucleate boiling heat transfer (NBHT) and CHF limits were obtained with higher subcoolings. The CHF was enhanced by ~49–102% on the Cold Spray coated vessel compared to a bare vessel. Kwark et al. [16] investigated the effects of pressure, inclination angle and heater size on the pool boiling of water using Al_2O_3 nanoparticle coated flat surfaces. The CHF was enhanced by ~70% when the inclination angle was increased from 45 to 180°, with the CHF enhanced by about 220% when $\theta = 0^\circ$. They stated that the better wettability of the nanocoated surface, especially its ability to continuously rewet the base of the growing bubbles, was the main cause of the enhancement. Jun et al. [13,14] investigated the NBHT and CHF of surfaces sintered with micro porous copper coatings which was called High-temperature Thermally-Conductive Microporous coating (HTCMC). The effects of inclination angle and particle size were studied using saturated water. The CHF decreased linearly as the inclination angle decreased from 90° to 10° and then declined more abruptly from 10° to 0°. The CHF of the HTCMC at 0° was 1.3–1.4 MW/m^2, which was about 4.5 times higher than the CHF on a plain surface at the same inclination angle.

Mori et al. [17,18] significantly enhanced the CHF by attaching a honeycomb porous plate (HPP) to a horizontal heated surface with the CHF increased dramatically as the porous plate thickness was reduced. The heat flux reached 2.5 MW/m^2 on one HPP, which was approximately 2.5 times that of the plain surface (1.0 MW/m^2). The CHF enhancement was attributed to the HPP providing strong capillary suction that supplied liquid to the heated surface and to the surface separating the liquid and vapor flow paths by vapor escape channels.

Zhong et al. [20] proposed a structured surface with interconnected grooves and triangular array cavities (IGTAC) to enhance the boiling heat transfer and CHF in saturated water. The CHF was increased by more than 102% on the structured surface which formed a liquid vapor conversion path with the cavities as stable nucleation sites and interconnected grooves as the cooling water supply pathways, which significantly enhanced the heat transfer and the CHF.

There are several other means to enhance the CHF, such as nanofluids and thermal insulation. The use of nanofluids to enhance the ERVC capability during a severe accident for advanced light-water reactors was proposed by Buongiorno et al. [22] and Pham et al. [23]. The CHF was enhanced by ~40% in an alumina-based nanofluid compared to deionized water [22]. The 0.05% Al_2O_3 + 0.05% CNT nanofluid significantly enhanced the CHF (32–123%) compared to deionized water [23], but the nanofluid stability is a great challenge for the ERVC system.

The effect of thermal insulation on the CHF was investigated by Yang et al. [24] and Noh and Suh [25]. Yang et al. [24] investigated the CHF on the outer surface of the lower head with scaled APR1400 thermal insulation in the SBLB facility. The results showed that the local CHF could be enhanced by 200–330% over a plain vessel using an enhanced insulation structure with micro porous coatings. Noh and Suh [25] measured the CHF on the outer surface of a 1/10 scaled APR1400 hemispherical vessel with thermal insulation in the Corium Ablation Stopper Apparatus (CASA). The results showed that the CHF reached about 1.5 MW/m^2 in the metal layer with the focusing effect.

An interconnected grooves and triangular array cavities structured surface enhanced the CHF by at least 102% compared to the plain surface [20] on a one dimensional (1D) inclined surface. In this study, the boiling heat transfer and CHF are measured on a 3D scaled vessel outer surface using saturated deionized water at atmospheric conditions. Two vessels with a plain surface and a structured surface were tested, with the boiling heat transfer rate and CHF significantly enhanced on the structured surface.

2. Experiment

2.1. Experimental set-up

The experimental system shown in Fig. 1 had a heating system with liquid metal as the intermediate heat transfer medium in a scaled vessel to investigate the boiling heat transfer and CHF on the 3D downward facing surface. The liquid metal was heated by heaters and circulated inside the vessel with the heat then transferred to the lower head by convection. The outer surface of the lower head was cooled by boiling heat transfer in the water pool. The steam was condensed by a condenser with the condensed water flowing back into the reservoir. The arrows in Fig. 1 show the liquid metal flow direction, which was driven by an impeller driven by a variable frequency motor. A photograph of the experimental apparatus is shown in Fig. 2. The 15 cartridge heaters were powered by a 226.5 kW AC power supply at 380 V. Each cartridge heater had a power rating of 15.1 kW at 380 V. The heaters were distributed in the vessel as illustrated in Fig. 3. Each cartridge heater was about 1.3 m in length and 19 mm in diameter. The wall heat flux on the vessel outer surface was controlled by adjusting the heating power. The voltages and currents were recorded by the data acquisition system to calculate the heating power.

Tin (Sn) was selected as the intermediate heat transfer medium because its melting point is 231.9 °C, and it is nontoxic. The tin spheres had diameters of 25 mm. At the beginning of this experiment, the tin spheres were placed in the molten pool which was heated by three heaters at low power. Each cartridge heater had a power of 5.5 kW at