Experimental Thermal and Fluid Science 68 (2015) 442–451

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Experimental study of saturated pool boiling from downward facing surfaces with artificial cavities

Dawen Zhong, Ji'an Meng *, Zhixin Li, Zengyuan Guo

Key Laboratory of Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, PR China

ARTICLE INFO

Article history:
Received 29 September 2014
Received in revised form 21 April 2015
Accepted 2 June 2015
Available online 18 June 2015

Keywords:
Pool boiling
Downward facing surface
CHF
Surface with artificial cavities
Heat transfer enhancement

ABSTRACT

Saturated pool boiling heat transfer rates were measured from downward facing and inclined surfaces with artificial cavities to study the effects of inclination angle and cavity structures on the wall superheat and critical heat flux (CHF). The inclination angles were 5°, 30°, 45°, 60°, and 90° (vertical), the artificial cavities were cylinders with diameters of 0.25 mm, 0.5 mm, and 1 mm and depths of 1 mm and 2 mm and center-to-center spacings of 8 mm, 4 mm, and 2 mm. The results show that the CHF increases as the inclination angle increases. Smaller inclination angles have higher wall superheats at a given heat flux. The structured surface had significantly smaller wall superheats than a plain surface. For the same cavity spacing and cavity depth, a larger cavity diameter gave a higher CHF. There was an optimal cavity depth that gave the highest CHF for given cavity diameter and spacing. The CHF increased as the cavity spacing decreased for a given cavity diameter and depth with larger cavity diameters leading to larger increases in the CHF. Compared with the plain surface the CHF increases on the downward-facing surfaces with cavities were not significant.

1. Introduction

Since the Three Mile Island accident, researchers have found that a pressure vessel immersed in coolant can provide sufficient heat transfer to provide in-vessel retention (IVR) of a core melt. In-vessel retention is a key severe accident management strategy used at some nuclear power plants which has been proposed for some advanced light water reactors. One method to achieve in-vessel retention is external reactor vessel cooling which involves flooding the reactor cavity to submerge the reactor vessel to cool the core debris which has relocated in the vessel lower head using passive cooling during a severe accident [1]. The key point to ensure that the waste heat generated by the fission products is completely removed by pool boiling heat transfer is to have the wall heat flux from the core melt not exceed the CHF for boiling on the vessel outer surface. Therefore, the variations of the CHF with angle must be known and the surface should be designed to enhance the boiling heat transfer on the outer surface of the pressure vessel.

There have been many studies of the effect of the inclination angle on the CHF for pool boiling. Styrikovich and Polyakov [2] first studied the effect of orientation on the pool boiling CHF in water, benzene and various alcohols and showed that changing the inclination angle, θ, of the hot surface from 180° to 90° reduced the CHF by 8% with the CHF at $\theta = 0°$ being 40% lower than that on an upward facing hot surface. Storr [3], Marcus and Dropkin [4], and Githinji and Sabersky [5] found that the CHF increased as the orientation changed from an upward-facing horizontal surface (180°) to vertical (90°). Marcus and Dropkin [4] attributed this to the increased agitation of the superheated boundary layer due to the increased path length of the departing bubbles along the surface. Githinji and Sabersky [5] and Ishigai et al. [6] showed that the CHF decreased rapidly as the orientation changed from vertical to downward-facing horizontal due to the coalescing bubbles impeding liquid wetting the hot surface. Vishnev [7] correlated the effect of orientation on the CHF for water and liquid helium pool boiling as:

$$\frac{q_{CHF}}{q_{CHF,180}} = \frac{(\theta + 10)^{0.5}}{190^{0.5}} \tag{1}$$

Nishikawa et al. [8] investigated nucleate pool boiling on a copper flat plate with orientations of 5–180°. They performed the experiments with saturated pool boiling of water at atmospheric pressure to investigate the effect of surface configuration on the nucleate boiling heat transfer. Their experiments showed that the effect of orientation was significant in the low heat flux region

* Corresponding author at: Department of Engineering Mechanics, School of Aerospace Engineering, Tsinghua University, Beijing 100084, PR China. Tel./fax: +86 10 62773776.

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

http://dx.doi.org/10.1016/j.expthermflusci.2015.06.003
0894-1777/

Nomenclature

A	surface area (m^2)
$C_{f,w,sat}$	empirical constant in Eq. (8)
d	cavity diameter (m)
D_h	equivalent heated surface diameter (m)
g	gravitational acceleration (m/s^2)
h	cavity depth (m)
h_{fg}	latent heat of vaporization (J/kg)
I	electric current (A)
L	width of the hot surface
q	heat flux (W/m^2)
q_{CHF}	critical heat flux (CHF) (W/m^2)
$q_{CHF,180}$	CHF for ordinary pool boiling on an upward-facing surface (180°) (W/m^2)
Q	heat transfer rate (W)
s	channel gap size (m)
S	cavity center-to-center spacing (m)
T	temperature (°C)
V	voltage (V)
Greek letters	
θ	inclination angle (°) (90°: vertical, 0°: downward-facing)
σ	surface tension (N/m)
ρ	density (kg/m^3)
Δx	spacing between the thermocouple location and the heated surface (m)
λ	thermal conductivity of the copper block (W/m K)
Subscripts	
m	measured
f	saturated liquid
g	saturated vapor
w	wall

where the heat transfer coefficient increased when increasing inclination angle, and with little effect of orientation for high heat fluxes. They thought that there were two boiling heat transfer mechanisms for the inclined downward-facing surface. One was the sensible heat transport due to compulsory removal of the thermal layer by the elongated bubble rising along the surface, the other was the latent heat transport. Their analytical results indicated that the latent heat transport was the more important boiling heat transfer mechanism.

El-Genk and Guo [9] experimentally investigated the effect of inclination angle on the boiling heat transfer of water at atmospheric pressure using a 50.8 mm diameter copper disk. Their results showed that the CHF and minimum film boiling heat flux, as well as the corresponding wall superheat, increased with increasing inclination angle. The CHF and minimum film boiling heat flux for the downward facing surface were significantly lower than for the other inclination angles. Guo and El-Genk [10] later developed a CHF correlation as a function of the orientation:

$$q_{CHF} = (0.034 + 0.0037(180 - \theta)^{0.656})\rho_g h_{fg} \times \left[\frac{\sigma g(\rho_f - \rho_g)}{\rho_g^2}\right]^{0.25} \tag{2}$$

Theofanous and Syri [11] conducted a full-scale simulation 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. The results for ULPU-II showed that the variation of the CHF with the orientation seemed to be composed of two linear regions with the experimental data fit as:

$$q_{CHF} = \left\{ \begin{array}{ll} 0.5 + 0.0133\theta \ \mathrm{MW/m^2} & 0^\circ \leqslant \theta \leqslant 15^\circ \\ 0.54 + 0.0107\theta \ \mathrm{MW/m^2} & 15^\circ < \theta \leqslant 90^\circ \end{array} \right\} \tag{3}$$

Haddad [12] studied the downward facing boiling crisis on the outer surface of a hemispherical vessel using the subscale boundary layer boiling (SBLB) test facility at PSU. Transient quenching and steady state boiling experiments were performed for both saturated and subcooled conditions. The results were similar to those of Theofanous and Syri [11] with the CHF data correlated with the orientation angle for transient quenching boiling as:

$$q_{CHF} = 0.4 + 0.0084\theta - 1.96 \times 10^{-5}\theta^2 \tag{4}$$

Dizon et al. [13] used the SBLB facility to measure the CHF using a different vessel. Their results matched those obtained earlier by Haddad [12]. Their empirical correlation was:

$$q_{CHF} = 0.4312 + 6.807 \times 10^{-3}\theta \tag{5}$$

Chang and You [14] experimentally investigated the effect of orientation on saturated FC-72 pool boiling of a flush-mounted, micro-porous-enhanced square heater. Smaller inclination angles provided higher heat fluxes in the nucleate boiling regime for angles from 90° to 180°. The nucleate boiling heat transfer coefficient significantly increased at higher heat fluxes as the angle increased from 0° to 90°. This phenomenon was also observed by Rainey and You [15]. The CHF data of Chang and You [14] were correlated against inclination angle as:

$$\frac{q_{CHF}}{q_{CHF,180}} = 1.0 - 0.00120(180 - \theta)\tan(0.414(180 - \theta)) - 0.122\sin(0.318(180 - \theta)) \tag{6}$$

Yang et al. [16] investigated the effects of inclination angle and heated surface size on the CHF. The CHF generally increased as the angle increased with a transition angle at which the CHF changed rapidly. The measured CHF were lower for the wider test section due to the more difficult bubble removal.

Howard and Mudawar [17] observed the vapor behavior just prior to the CHF and divided the effects of the orientation into three regions: upward-facing ($120^\circ \leqslant \theta \leqslant 180^\circ$), near-vertical ($15^\circ \leqslant \theta \leqslant 120^\circ$) and downward-facing ($0^\circ \leqslant \theta \leqslant 15^\circ$) with each region having a unique CHF trigger mechanism.

Kim and Suh [18] conducted CHF experiments on a one-dimensional downward facing heated rectangular channel with gap sizes of 1, 2, 5 and 10 mm. The experiments also analyzed the effect of orientation on the CHF. A transition angle was also found at which the CHF changed rapidly. A semi-empirical correlation was developed for the near vertical gap boiling using dimensional analysis:

$$\frac{q_{CHF}/\rho_g h_{fg}}{\sqrt[4]{\sigma g \sin(\theta)(\rho_f - \rho_g)/\rho_g^2}} = \frac{0.17}{1 + 6.8 \times 10^{-4}(\rho_f/\rho_g)^{0.62}(D_h/s)} \tag{7}$$

Priarone [19] experimentally analyzed the effect of inclination angle on the nucleate boiling of FC-72 and HFE-7100 from a smooth copper surface for inclination angles from 5° to 180°. The results indicated that the heat transfer coefficient increased