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Visualization of boiling phenomena in inclined rectangular gap

Y.H. Kim [a], S.J. Kim [a], J.J. Kim [a], S.W. Noh [a], K.Y. Suh [a,*], J.L. Rempe [b], F.B. Cheung [c], S.B. Kim [d]

[a] *Department of Nuclear Engineering, Seoul National University, San 56-1 Sillim-dong, Gwanak-gu, Seoul 151-742, Republic of Korea*

[b] *Idaho National Engineering & Environmental Laboratory, Idaho Falls, ID 83415, USA*

[c] *Pennsylvania State University, University Park, PA 16802, USA*

[d] *Korea Atomic Energy Research Institute, Yuseong, Daejeon 305-600, Republic of Korea*

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Abstract

An experimental study was performed to investigate the pool boiling critical heat flux (CHF) in one-dimensional inclined rectangular channels by changing the orientation of a copper test heater assembly. In a pool of saturated water under the atmospheric pressure, the test parameters included the gap sizes of 1, 2, 5, and 10 mm, and the surface orientation angles from the downward-facing position (180°) to the vertical position (90°). Tests were conducted on the basis of the visualization of boiling phenomena in the narrowly confined channel and open periphery utilizing a high-speed digital camera. To prevent the heat loss from the water pool and copper test heater, a state-of-the-art vacuum pumping technique was introduced. It was observed that the CHF generally decreased as the surface inclination angle increased and as the gap size decreased. In the downward-facing position (180°), however, the vapor movement was enhanced by the gap structure, which produced the opposing result; that is, the CHF increased as the gap size decreased. Phenomenological characteristics regarding the interfacial instability of vapor layer were addressed in terms of visualization approaching the CHF. It was found that there exists a transition angle, around which the CHF changes with a rapid slope.

* Corresponding author. Tel.: +82 2 880 8324; fax: +82 2 889 2688.
E-mail address: kysuh@snu.ac.kr (K.Y. Suh).

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1. Introduction

A great deal of literature exists relating to the effect of surface orientation and gap size on the pool boiling heat transfer and critical heat flux (CHF) characteristics. The engineered results are applied to cooling of the electronic and power appliances, heat treatment of the metallic parts, and cooling of the superconductor coils. In view of nuclear reactor safety management, it is crucial to accurately predict the CHF and phenomenological boiling dynamics (Kim and Suh, 2000a,b; Yoon and Suh, 2000; Cho et al., 2000, 2004; Lee and Suh, 2003; Rempe et al., 2004a,b, 2003; Dizon et al., 2004; Cheung et al., 2004; Knudson et al., 2004). In the Three-Mile Island Unit 2 (TMI-2) accident, for instance, the lower part of the reactor vessel was overheated but then rather rapidly cooled down (Wolf and Rempe, 1993; Henry and Fauske, 1993; Suh and Henry, 1996a,b; Rempe et al., 2001). It was suggested that this rapid cooldown may have been due to cooling in a narrow gap, smaller than the order of centimeters, which may have formed between the solidified core debris and the reactor vessel lower head. To better quantify such cooling, experiments are being conducted to quantify the CHF associated with bubble behavior that may affect the entire state of the heat transfer mode. Various two-phase flow patterns are also observed to gain insights about the fundamental physics required to interpret the data. In this sense, one needs to design the CHF test sections to simulate both the confined and angle convertible channels.

Heretofore, a great deal of experimental studies have been reported concerning the heater surface orientation (Ishigai et al., 1961; Githinji and Sabersky, 1963; Nishikawa et al., 1984), in which several researchers have tried to interpret the CHF mechanism for pool boiling by correlating the CHF data into a generalized equation (Brusstar and Merte, 1994; Brusstar et al., 1997; Chang and You, 1996; El-Genk and Guo, 1993; Guo and El-Genk, 1992; Howard and Mudawar, 1999; Vishnev, 1974) and for flow boiling circumstance (Galloway and Mudawar, 1993; Gersey and Mudawar, 1995). Among them, El-Genk and Guo (1993) developed the following CHF correlation for water that considers orientation

$$q_{\mathrm{CHF}} = [0.034 + 0.0037(180 - \theta)^{0.656}]\rho_{\mathrm{G}} h_{\mathrm{LG}}[\sigma(\rho_{\mathrm{L}} - \rho_{\mathrm{G}})g/\rho_{\mathrm{G}}^{2}]^{0.25} \quad (1)$$

where q_{CHF} is the CHF in W/m^2, ρ_{L} and ρ_{G} are the saturated liquid and vapor densities in kg/m^3, h_{LG} is the latent heat of vaporization in J/kg, σ is the surface tension, g is the gravitational acceleration in m/s^2, and θ is the heater surface orientation angle in degrees. The function of angle θ varies with the working fluid. The correlation of other investigators (Vishnev, 1974; Brusstar and Merte, 1994; Brusstar et al., 1997) takes on a similar form. Recently, some researchers mentioned the existence of a transition angle at which the CHF decreases rapidly (Howard and Mudawar, 1999; Yang et al., 1997).

Also many investigators have attempted to predict the gap size effect on the CHF in various channels. Several correlations were generated in terms of the predominant functional variables (Chang and Yao, 1983; Chyu, 1988; Katto and Kosho, 1979; Kim et al., 2000; Monde et al., 1982). With the aid of dimensional analysis developed by Katto (1978), the following correlating