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Critical heat flux in various inclined rectangular straight surface channels

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ABSTRACT

One-dimensional experiments with three kinds of copper blocks were performed for an investigation of critical heat flux (CHF) to account for a ratio of heated length to gap size and twist angle as well as gap size and surface inclination angle ranging from the vertical (90°) to fully downward facing (180°) position effects in the rectangular channel. The CHF can be decreased if it is not easy for the bubble to escape from the heated surface. All parameters affecting the CHF (e.g., gap size, surface inclination angle, heated length to gap size ratio, and twist angle) affect the bubble escaping from the heated surface. Transition angles were spotted at which the CHF changes with a rapid slope, as the inclination angle is increased, which is consistent with the existing literature. A semi-empirical CHF correlation was developed for inclined narrow rectangular channels through a dimensional analysis. The correlation reflected from the best-estimate CHF values can be provided for realistically assessing the thermal margin to a failure of the lower head during a severe accident involving a relocation of the molten core material in a reactor vessel.

1. Introduction

After the Three-Mile Island Unit 2 (TMI-2) accident in 1979, Wolf and Rempe [1] concluded that at least 45% of the core, 62 tons, were melted by inadequate core cooling, and that nearly 19 tons of the core material was relocated to the lower head of reactor vessel. Post-accident examinations indicated that about half of that material formed a solid layer near the lower head. The lower head was overheated but then rather rapidly cooled down, and the reactor vessel integrity could be maintained [2,3]. This accounted for the possibility of cooling in the narrow gap on the order of millimeters that may have been formed between the solidified core debris and the reactor vessel lower head. For this reason, research on the critical heat flux (CHF) during pool boiling in confined channels is important as a fundamental study of the CHF phenomenon as well as its application to industrial problems. Hence, additional data are needed to quantify a CHF in narrow gaps and gain insight about the potential for in-vessel retention (IVR), as shown in Fig. 1.

Many investigators have attempted to correlate the geometric effect on the CHF, and have carried out a great deal of studies on the CHF and derived correlations with the CHF data for various fluids and conditions during the last decades. Concerning the heater surface inclination angles, several researchers attempted to interpret the CHF mechanism by correlatinheir own or other CHF data into generalized equations in pool boiling [4–16] and flow boiling [17,18]. Some researchers particularly mentioned the existence of a transition angle around which the CHF changes rapidly [8,14,15,19]. Many other pool boiling CHF studies examined the inclination effect to find that the CHF decreases as the inclination angle changes from upward facing horizontal (0°) to vertical (90°) to downward facing horizontal position (180°).

Howard and Mudawar [14] compared the existing CHF data with the correlations by Vishnev [6], Guo and El-Genk [8], El-Genk and Guo [9] and Chang and You [13], and the empirical model described by Brusstar and Merte [11] and Brusstar et al. [12] for cryogenic and noncryogenic fluids. They modeled the near vertical regime based on the following observations. At high heat flux conditions, near vertical pool boiling exhibits vapor production and vapor flow patterns similar to those found in flow boiling. They claimed that the model shows good agreement with the CHF data for different fluids, and is also accurate in predicting the angle of transition between the near vertical and downward facing regimes.

Fig. 2 shows a comparison between the CHF data and correlations [6,9,12,13,20] considering the surface inclination effect on the CHF. Nondimensionalized correlations in the cited literature are seen to shift for differing fluids, which appears to support El-Genk and Guo's assertion [9] that different correlations be used for different fluids in describing the effect of orientation on the CHF. It is difficult for one nondimensionalized equation to correlate

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Nomenclature

A_1	constant
A_2	coefficient
A_3	exponent
A_4	exponent
B_1	constant
B_2	coefficient
B_3	exponent
B_4	exponent
C_1	constant
C_2	coefficient
C_3	exponent
C_4	exponent
C_p	specific heat (J/kg K)
h_{fg}	latent heat of vaporization (J/kg)
D_h	equivalent heated diameter (m)
D_e	equivalent diameter (m)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/K m^2)
l	heated length (m)
s	gap size (m)
w	heated width (m)
q	heat flux (W/m^2)

Greek letters

θ	inclination angle (°)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

CHF	critical heat flux
f	saturated liquid
g	saturated vapor

the experimental data at various inclination angles from vertical to downward facing horizontal position (180°), as presented in Fig. 2, because the dimensionless CHF values for the gap size tend to spread as the inclination angle increases. The nondimensionalized correlation can be affected not only by different fluid properties but also by the surface inclination effect. Note also that the Monde et al. [20] and Chang and You [13] correlations provide upper and lower bounds, respectively, for the data taken from the GAMMA RC (Gap Apparatus Mitigating Melt Attack Rectangular Channel) test [21–23].

The bubble behavior has various modes in confined channel geometry. From the viewpoint of a microlayer heat transfer, a number of investigations have suggested that the heat transfer rate decreases when the bubble is confined by the channel geometry. To investigate the geometrical effect on heat transfer, some authors have performed experiments for natural convection boiling, pool boiling, and gap boiling.

Several investigators [20,24–30] have conducted research to predict the gap size effect on CHF in various channels, where several essential correlations were generated in terms of the predominant functional variables. Experiments were performed on the boiling of saturated water at atmospheric pressure in a space bounded by two horizontal coaxial disks with lower-disk heating, but no correlations of the CHF data were presented [31].

Using a copper plate forming the vertical rectangular channel with a heated-length-to-gap-size ratio l/s of less than 120, Monde et al. [20] performed CHF experiments for various gap sizes from 0.45 to 7.0 mm in water, ethanol, R-113 and benzene as working fluids. They developed a generalized correlation of the CHF data which agrees with an uncertainty of about ±20%. Bonjour and Lallemand [32] developed a generalized correlation by modifying the Monde et al. (1982) correlation to take into account the influence of pressure.

Aoki et al. [33] experimented with a vertical annular tube for a gap size ranging from 0.2 to 1.5 mm for both open and closed bottoms. Similarly to Katto and Kosho [27], they concluded that the transition heat flux to the drying and wetting region can be correlated by the equivalent gap length defined in terms of the cross-sectional area of the open end, and it decreases as the gap length increases.

Mishima and Nishihara [34] performed flow CHF experiments for water employing three different channel geometries: an annulus, a rectangular duct, and a round tube. They concluded that the effect of the channel geometry is significant at intermediate mass velocities. They claimed that the CHF occurs because of a counter-current flow limitation (CCFL) with low mass flux (the minimum value occurs at a mass flux of 200 kg/m^2 s or less downstream), and that the effect of inlet subcooling can be neglected for subcooling exceeding 70 °C. Fujita et al. [35] examined the boiling heat transfer of water at atmospheric pressure under conditions of a small gap and high heat flux. They observed that the bubbles were flattened, leading to a temporary dryout.

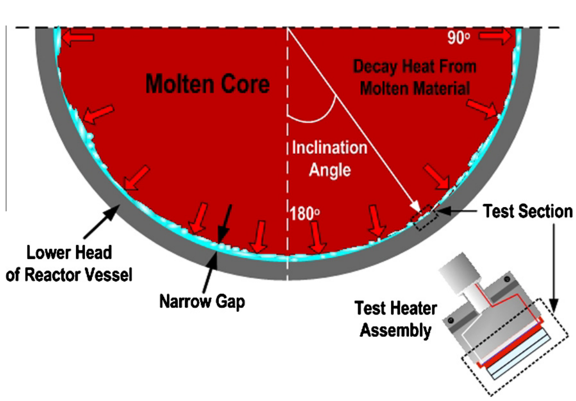

Fig. 1. Schematic diagram of gap boiling in lower head of reactor vessel.

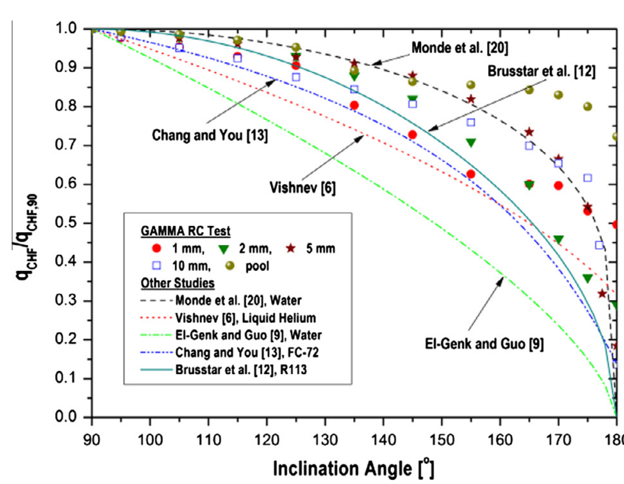

Fig. 2. Effect of surface inclination angle on CHF.