Film Boiling Heat Transfer from Inclined Downward Heated Flat Surfaces

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1. Introduction

The current literature survey [1-4] revealed that as the inclination angle increases from the bottom up, the vapor film thickens, the vapor flows faster, and the interfacial wavy motion occurs in the vapor film. The interfacial waves accordingly increase in wavelength, eventually becoming unstable. The vapor film thickness and interfacial velocity are calculated pursuant to the laminar film boiling analysis.

2. Methods and Results

In this section a new semi-empirical correlation is developed from the measured heat transfer coefficients and the visualized interfacial velocity. This empirical correlation is compared with other experimental results to estimate its applicability.

2.1 Semi-Empirical Correlation

A new semi-empirical model correlation is based on the laminar film boiling analysis and vapor film Reynolds number. The semi-empirical correlation has two unknown parameters: the layer thickness ratio and the critical vapor film Reynolds number.

Kolev [2] assumed the equal layer thickness of both the liquid momentum and temperature boundary layers. However, the assumption is only adequate to highly subcooled film boiling. There is no liquid thermal boundary layer in saturated film boiling. Bui and Dhir [1] and Kolev [2] obtained the film boiling heat transfer coefficient from the zero interfacial velocity condition.

Kim [5], on the other hand, has found that the interfacial velocity was not zero. Therefore, the layer thickness ratio could not be obtained from previous investigations. The unknown parameters are obtained from the visualized interfacial velocities and the measured heat transfer coefficients [5]. Measured heat transfer coefficients have uncertainties of ± 8 %. In contrast the qualified interfacial velocity has relatively large uncertainties of ± 17~22 %. The critical vapor film Reynolds number may be written as follows

$$\mathrm{Re}_{cr} = \frac{\rho_v u_i \delta_{v,\max}}{\mu_v} = 9.5\ (\pm 13\%) \tag{1}$$

The layer thickness ratio over the sum of the viscosity ratio and the layer thickness ratio is 0.114 ± 10 %.

Two parameters are independent of the inclination angle and the wall superheat from the test results. Therefore, the angular dependency of the maximum vapor film thickness and the angular wavelength can be expressed as

$$\delta_{v,\max}(\theta) = \delta_{v,\max}\left(\frac{\pi}{2}\right)(\sin\theta)^{-1/3} \tag{2}$$

$$\lambda(\theta) = \lambda_{90}(\sin\theta)^{-1/3} \tag{3}$$

If the characteristic length of the angular Nusselt number is the wavelength on the vertical plate, the angular Nusselt number may be written as

$$\begin{aligned} Nu_{\lambda_{90}}(\theta) &= \frac{h(\theta)\lambda_{90}}{k_v} = \frac{h(\theta)\lambda(\theta)}{k_v}(\sin\theta)^{1/3} \\ &= \frac{2}{3}\left(\frac{Ra_{\lambda_{90}}}{n_{FB}Ja}\right)^{0.25}(\sin\theta)^{1/3} \end{aligned} \tag{4}$$

2.2 Comparison with Experimental Results

Figures 1 (a) to (c) summarize the heat transfer coefficients [5] obtained from the inclined flat plates for varying wall superheats. The test results are compared with the laminar film boiling [6] and laminar wavy film boiling [3] correlations.

In all the cases examined the laminar wavy film boiling correlation always is in better agreement with the test data than the laminar film boiling correlation. The interfacial wavy motion is the most governing mechanism that determines the film boiling heat transfer coefficients for relatively large test sections exceeding a few centimeters.

The Kelvin-Helmholtz instability limits the increase of vapor film thickness so that the film boiling heat transfer coefficients are greater than those determined by the laminar film boiling analysis.

The large inclination angle widens the difference between the experimental data and laminar film boiling heat transfer coefficients. This results from a more active interfacial wavy motion of film boiling heat transfer at larger inclination angles.

The new semi-empirical correlation is compared against other experimental results. Figure 2 compares the current result against other experiments utilizing water.

Bui and Dhir [1] measured the film boiling heat transfer coefficients on the vertical surface 0.103 m long. Okkonen et al. [4] measured the film boiling heat transfer coefficients on the vertical surface 1.5 m long spanning a wide range of wall superheat.

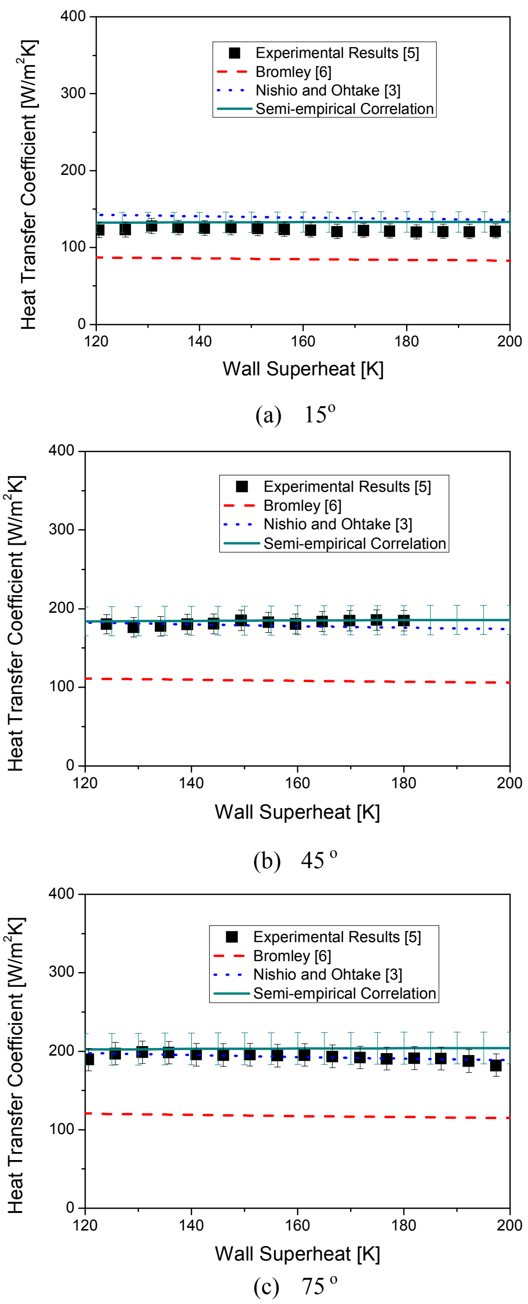

Figure 1. Film boiling heat transfer coefficients [5]

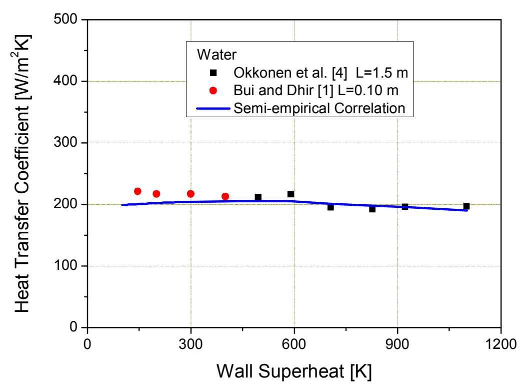

Figure 2. Film boiling heat transfer coefficients [1, 4]

3. Conclusion

All the experimental film boiling heat transfer coefficients with water were greater than those given by the numerical solution for the laminar film boiling due mostly to limitation on the vapor film thickness caused by the interfacial wavy motion. The interfacial wavy motion resulting from the Helmholtz instability plays an important role in evading decrease in the film boiling heat transfer coefficient with the increasing geometrical size. As expected, the film boiling analysis with the interfacial wavy motion showed excellent agreement with the experimental data from the downward heated flat plates.

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