Azimuthally Curved Film Boiling Heat Transfer from Downward-facing Hemispheres

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1. Introduction

The laminar film boiling analysis has been found to underpredict the film boiling heat transfer coefficients on downward-facing hemispheres. Many researchers asserted that it could be due to the interfacial wavy motion with the Helmholtz instability. Kim et al. conducted DELTA SS (Downward Ebullient Laminar Transient Apparatus Spherical Surface) experiments to determine the effect of diameter on film boiling from downward-facing hemispheres made of copper with diameters 120 and 294 mm. [1] For the 120 mm copper most region of the downward-facing area was typified by the laminar vapor film. The interfacial wavy regime spanned a greater portion of the 294 mm test section. The stainless steel has quite lower thermal conductivity than copper. This experiment is performed to obtain the effect of inclination angles and curvature on film boiling heat transfer. The test results are compared with the analytical results of the laminar film boiling analysis.

2. Experimental Setup

Figure 1 presents the stainless steel test section whose diameter and thickness are 294 and 30 mm, respectively. The stainless steel pipe was welded on top of the hemisphere to prevent water from ingress to the test section. Its outer, inner diameter and height are 292, 289 and 100 mm, respectively. The outer diameter of the pipe is less than that of the hemisphere. This explains why there is no release of bubbles at the top of the hemispheres. Eighteen thermocouples were installed at 0° (bottom), 10°, 20°, 30°, 40°, 50°, 60°, 70° and 80° near the outer and inner surfaces of the test section. The angular film boiling heat fluxes and heat transfer coefficients were obtained from the two-dimensional transient temperature profiles.

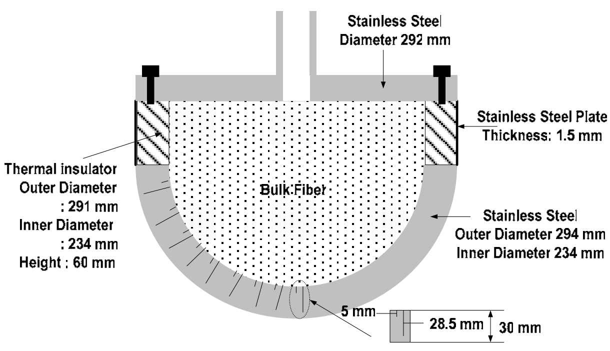


Figure 1. DELTA SS stainless steel test section

3. Test Results

Figure 2 shows the smoothed temperature history in the DELTA SS stainless steel test section. Note that temperature decreases vary along the azimuthal angles. The variation results from variation in the angular film boiling heat transfer coefficients. Initially, temperature of the test section decreases through film boiling heat transfer with a gradual gradient. In the transition and nucleate boiling regimes, the temperature drops at a much faster rate. The equatorial part first reaches the nucleate boiling regime, which then expands downward gradually. It takes about 200 s for transition boiling to propagate from the equator to the bottom as captured in Figure 3.

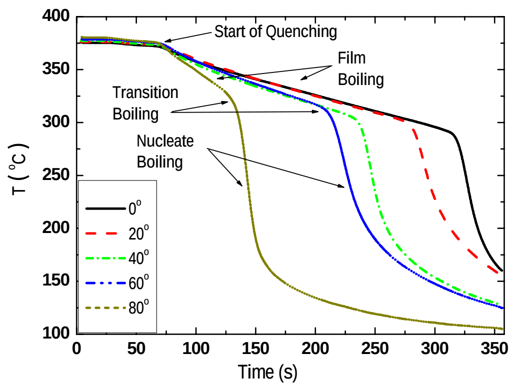
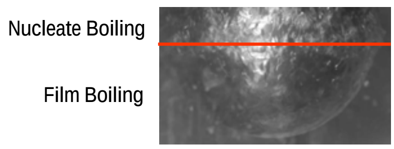
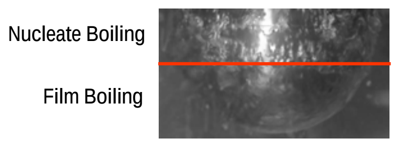


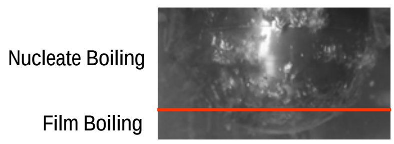
Figure 2. Temperature history



(a) Transition boiling near the equator



(b) Propagation of transition boiling downward



(c) Propagation of transition boiling to the bottom

Figure 3. Quenching process

For a wall superheat of 253.7 K, the heat transfer coefficients obtained are plotted and compared with those from the laminar film boiling analysis in Figure 4. For the analysis of laminar film boiling, four equations are used as follows. [2, 3]

$$h = \frac{k_v}{\delta_v} \tag{1}$$

where h: heat transfer coefficient [W/m^{2}K]
k_v: thermal conductivity of vapor [W/m K]
δ_v: vapor film thickness [m]

$$\delta_v = R\, n_{FB}^{0.25} \left(\frac{128 Ja}{Ra} \right)^{0.25} \left[\frac{\int_0^{\theta} (\sin\phi)^{5/3} d\phi}{(\sin\theta)^{8/3}} \right]^{0.25} \tag{2}$$

where R: radius of test section [m]
Ra: Rayleigh number
Ja: Jacob number

$$n_{FB} = \left(\frac{f+4\xi}{f+\xi} \frac{1+0.5Ja\dfrac{f+3\xi}{f+4\xi}}{1+r_r} \right)^{-1} \tag{3}$$

where r_r: ratio of radiation heat fluxes due to conduction and radiation

$$f = \mu_l / \mu_v \quad \xi = \delta_l / \delta_v \tag{4}$$

where μ_l: viscosity of liquid [N s/ m^2]
μ_v: viscosity of vapor [N s/ m^2]
δ_l: liquid boundary layer thickness [m]

In this analysis there are two main factors: boundary layer thickness ratio (ξ) and viscosity ratio (f) between water and vapor. When the boundary layer thickness ratio is zero, the interfacial velocity is zero. The infinite layer thickness ratio signifies the zero interfacial shear stress. Thus, the actual film boiling heat transfer coefficients are bounded between the cases of layer thickness ratios of zero and infinity. [3]

In Figure 4 the experimental data skyrocket at certain angles. That is, undulating heat transfer coefficients are observed as the azimuthal angle increases. They come from the Helmholtz instability limiting the vapor film thickness. As the angle increases starting from the bottom, the vapor film continues to thicken, the vapor flow picks up, and the interfacial wavy motion occurs in the vapor film. The interfacial waves accordingly increase in wavelength, eventually becoming unstable. Nishio et al. and Kolev tried to the point where film broke up. [4, 5] They developed the film boiling model with the interfacial wavy motion by the Helmholtz instability on flat plates. The Helmholtz instability wavelength is the key factor in the local film breakup on flat plates. However, it cannot be used on spheres, because the wavelength tends to vary on the curved downward surfaces. Hence, the vapor film Reynolds number was chosen as the parameter for simulation of the interfacial wavy motion on spheres. [1] Sensitivity analysis is being performed varying the critical values to obtain the proper critical vapor film Reynolds number.

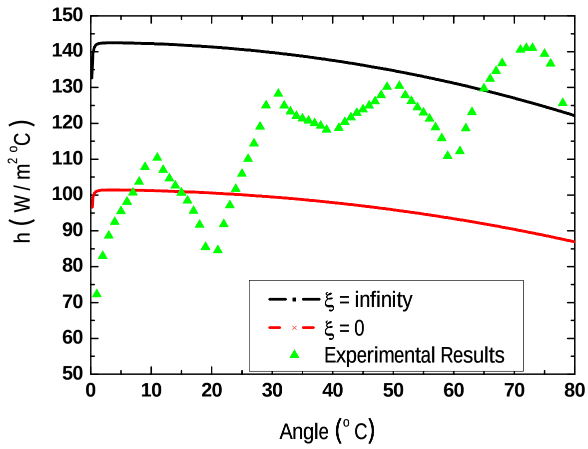


Figure 4. Angular heat transfer coefficients

4. Conclusion

A series of tests were performed to obtain the effect of inclination angles and curvature on film boiling heat transfer utilizing the DELTA SS stainless steel test section with diameter and thickness of 294 and 30 mm, respectively. The measured heat transfer coefficients differed from the results of the laminar film boiling analysis owing to the interfacial wavy motion. Local breakup of the film was observed. Additional work is being performed to more precisely predict the angular film boiling heat transfer from the downward-facing hemispheres based on more reliable engineering criteria.

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