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Film Boiling Heat Transfer from Downward-facing Hemisphere DELTA

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Abstract

The strategy of in-vessel retention through external vessel cooling (IVR-EVC) was suggested to protect the lower head from being overheated due to relocated material from the core during a severe accident. The cavity flooding was selected because of relatively simpler installation than flooding within the thermal insulator. However, the cavity flooding tends to take much more time than flooding within the thermal insulator. The differential time between the two flooding strategies was estimated to be as large as forty minutes in a typical pressurized water reactor (PWR). It is thus questionable whether the reactor vessel could indeed be soaked prior to relocation of the molten core unless the core damage state is recognized early enough to allow for timely flooding of the lower head. Once the core material has been accumulated prior to flooding, the initial heat removal mechanism may most likely be transient, turbulent film boiling of water. The current understanding is mostly limited to steady-state, laminar film boiling on the sphere, however. Further the correlations were developed from the test sections much smaller than the reactor vessel. The laminar film boiling heat transfer coefficients will tend to underestimate the actual heat transfer from the lower head. In this study the film boiling heat transfer coefficients for a downward-facing hemispherical surface are measured from quenching tests. The test section is made of copper to maintain the Biot (Bi) number below 0.1. The results of this experiment are compared with predictions by the laminar film boiling correlations. It is observed that the higher thermal conductivity of copper results in the lower wall superheat and heat flux at the minimum heat flux condition in the tests. Re_d is not large enough for the film boiling region to be turbulent in this experiment. Thus, the experimental values are greater than the numerical results because of the Helmholtz instability. The boiling mechanism on the downward-facing hemisphere is visualized through a digital camera.

1. Introduction

During the basic design for the APR-1400, the external cooling of the reactor vessel lower head was chosen as the severe accident management strategy, and is currently in the process of design optimization and licensing. The cavity flooding was selected as the external

vessel cooling method because of the relatively simpler installation than that of flooding within the thermal insulator. In fact, the IVR-EVC concept had not been considered during the initial design phase of the APR-1400. Thus several issues surfaced while applying the IVR concept at a later stage of design. One of these issues was the delayed flooding of the reactor vessel because of the large volume between the cavity floor and the lower head. The cavity flooding and flooding within the thermal insulator may take as much as forty minutes. It is thus not certain that the flooding time is shorter than that of relocation of the molten core down to the lower plenum of the reactor vessel. Hence the initial heat removal mechanism for the external vessel cooling will most likely be film boiling. However, the film boiling heat transfer coefficients for a sphere were applied to the liquid surrounding a small hot metal particle. The film boiling heat transfer coefficients of the former correlations will be less than the actual value for the reactor vessel lower head.

Bromley [1], Koh [2], Sparrow and Cess [3], and Nishikawa and Ito [4] performed the studies of film boiling on the vertical plates. They applied the various boundary conditions to prediction of film boiling heat transfer coefficients. Generally, the boundary conditions at the interface between the vapor film and bulk liquid were divided into the zero interfacial velocity and the same interfacial shear stress. Frederking and Clark [5], Sakurai et al. [6], Tou and Tso [7] studied the model for the laminar film boiling heat transfer coefficients on spheres based on the previous analytic solutions for those on the vertical plates.

The film boiling heat transfer coefficients were measured higher for relatively long vertical plate than those predicted for the laminar film boiling (Bui and Dhir [8]). Dhir and Purohit [9] measured film boiling heat transfer coefficients 50~60 % higher than those predicted by the laminar plane interface theory from spheres. Kolev [10] developed the correlation with Helmholtz instability at vertical plates and spheres. Experimental data are nonexistent for the downward-facing hemisphere on a large scale, however. Generally, the film boiling heat transfer coefficients were measured by the quenching experiments. In this study, the heat transfer coefficients were measured from the quenching experimental facility DELTA (Downward-boiling Experimental Loop for Transient Analysis) utilizing the measured temperature values.

2. Numerical Analysis

2.1 Governing Equations

The assumptions adopted in this analysis include the incompressible flow model, the Boussinesq approximation, neglected inertia and convection terms, the laminar film layer, fluid motion in the boundary layer, vapor material properties independent of temperature, negligible viscous heating, stable and thin film layer, smooth wall surface, and negligible effects of interfacial wave. Then the governing equations for the vapor film in the spherical coordinate system take on the following form

$$\frac{\partial}{\partial \mathbf{q}}(u \sin \mathbf{q}) = 0 \quad (1)$$

$$\frac{\mathbf{m}}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial u}{\partial r} \right) = g(\mathbf{r}_l - \mathbf{r}_v) \sin \mathbf{q} \quad (2)$$

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right) = 0 \quad (3)$$

where u is the angular velocity, μ is the viscosity of vapor, ρ_l and ρ_v are respectively the density of liquid and vapor, and T is temperature of the fluid in the film layer.

2.2 Boundary Conditions

Two boundary conditions are applied for this analytical solution. Case 1 assumes that the interfacial velocity is zero. Case 2 assumes that the interfacial shear stress has the same value in the vapor film and in the bulk liquid and that the value is small enough to be neglected. The boundary conditions other than the interfacial velocity and shear stress include Frederking and Clark [5]'s condition. The boundary conditions are thus taken as follows

$$\begin{aligned} r = R &\rightarrow u = 0, T = T_w \\ r = R + d &\rightarrow T = T_{sat}, dw_v = dw_l = dw_i = d \left(\int_R^{R+d} u 2pR \sin q dr \right) \end{aligned} \quad (4)$$

$$r = R + d \rightarrow u = 0 \quad \text{case(1)}, \mathbf{t}_v = \mathbf{t}_l = -\mathbf{n} \left(\frac{\partial u}{\partial r} \right) = 0 \quad \text{case(2)}$$

$$r = R \rightarrow k \left(-\frac{\partial T}{\partial r} \right) 2pR^2 \sin q = h_{fg} \mathbf{r}_v dw_i \quad (5)$$

where R is the radius of the hemisphere, w is the interfacial mass flow rate, h_{fg} is the latent heat of vaporization, k is the thermal conductivity of vapor, d is the thickness of the film layer, and T_w and T_{sat} are the wall temperature and vapor saturation temperature, respectively.

The film boiling heat transfer coefficient in case 1 is lower than that in case 2. Generally, the actual laminar film boiling heat transfer coefficient is a mid-value within the values in cases 1 and 2 (Tou and Tso [7]).

2.3 Average Nu

The velocity and temperature profiles are derived from Eqs. (2), (3) and (4). The local thickness of the film layer is determined from Eq. (5). The velocity and temperature profiles are obtained by numerical analysis. Finally the average Nu is calculated from the dimensionless temperature gradient at the wall as follows

$$Nu = 2 + \int_0^{\pi/2} R \frac{\sin q}{d} dq \quad (6)$$

Integrating Eq. (6), the new laminar film boiling correlation for the downward-facing hemisphere is

$$Nu = 2 + C \left(\frac{Ra}{Ja} \right)^{0.25} \quad (7)$$

where constant C is 0.696 and 0.985 in cases 1 and 2, respectively.

3. Experimental Setup and Data Reduction

The hemispherical test section had five K-type thermocouples. The epoxy bond was applied at the top of the holes to secure good contact between the thermocouples and the test section wall during installation of the stainless steel disk and the Fire Stop. The holes were drilled through the center of the stainless steel disk, stainless steel pipe and the Fire Stop to route the wall thermocouples to the HP-VXI E1413C data acquisition system. The material of the test section is copper to maintain Bi below 0.1 in the film boiling regime. In case of Bi less than 0.1 the conduction heat transfer in the solid may be neglected (Incropera and Dewitt [11]). Thus the experimental data could be compared with numerical analysis for the isothermal hemispherical surface. The thickness of the copper was 3 cm for data from the quenching experiment to equal the data from the steady-state experiment (Peyayopanakul and Westwater [12]). If the time to traverse the top 10 % of the boiling curve was greater than 1 sec, the boiling process was quasi-steady state (Dhir [13]). The test section's inner cavity was filled with bulk fiber and covered on top with the Fire Stop disk for thermal insulation. A stainless steel disk was fastened to the test section wall using eight stainless steel bolts. Figure 1 shows the cross-sectional view of the test section.

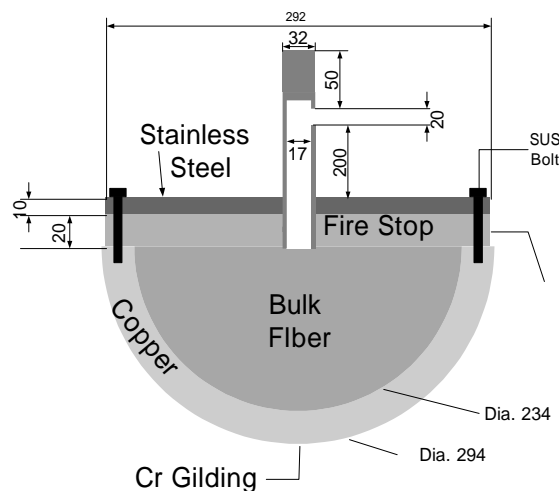


Figure 1 Cross-sectional View of Test Section

The quenching tank is of 1.00×1.00×1.10 m. A tank diameter must have 3.5 times the length as that of the test section to maintain the pool boiling without the effect of the size of the quenching tank (Westwater et al. [14]). It has large glass windows on one side for visual inspection and recording of the pool boiling on the hemispherical surface during quenching using the video camera. During the experiment the water in the tank was maintained at the saturated condition using four 10 kW and two 7 kW immersed electric heaters.

Prior to each quenching experiment, the distilled water in the tank was degassed by boiling for thirty minutes. The test section was heated up to 280°C. The heated test section was transferred from the furnace to the quenching tank by the automatic lift for thirty seconds. The heated test section was then submerged in the quenching tank, with its top surface kept 10 cm below the water level. Figure 2 shows the experimental facility DELTA.

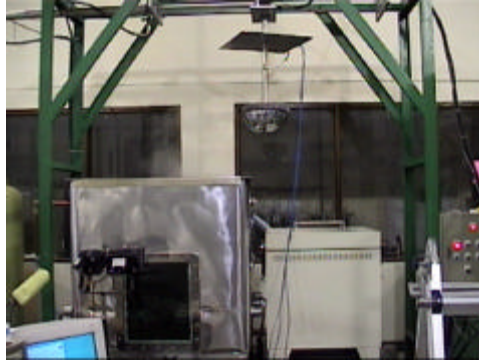


Figure 2 Picture of Experimental Facility DELTA

This experiment was designed for measurement of temperature profile pursuant to the film boiling heat transfer coefficient. Measured temperature history was smoothed by means of 10 points FFT-filter in Microcal Origin 6.0. The film boiling heat transfer coefficient was calculated from the smoothed temperature history as follows

$$h_{film} = \frac{rc_p G \Delta T}{\Delta t \Delta T_{sat}} - 0.75 h_{rad} \quad (8)$$

where ρ and c_p are the density and the specific heat of copper, G is the ratio of volume to outer area of the test section., ΔT , Δt and ΔT_{sat} are respectively the temperature differences in the time step, time step size, and wall superheat of the test section, and h_{rad} is the radiation heat transfer coefficient calculated from the wall temperature.

4. Results and Discussion

Figure 3 shows the smoothed temperature history from the DELTA experiments. Initially the temperature of the test section is reduced through film boiling heat transfer. Thus, the slope of temperature decrease is lax in the film boiling region. In the transient and nucleate boiling region, the temperature drops at a much faster rate.

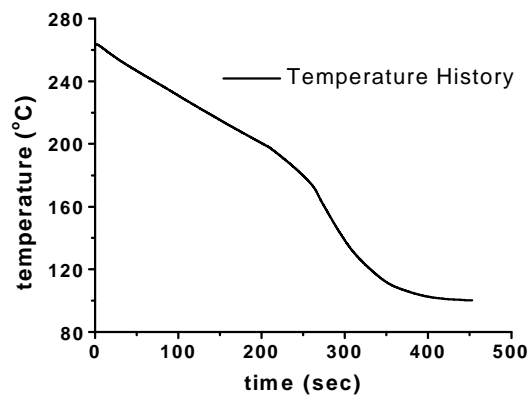


Figure 3 Temperature History

Figure 4 presents the heat flux in relation with the wall superheat. The minimum heat flux is about 20 kW/m^2 . The value is lower than reported by El-Genk and Gao [15]. Their experiments for aluminum and 303E stainless steel showed that the minimum heat flux for 303E stainless steel is larger than that for aluminum. The wall superheat at the minimum heat flux is about 100 K . The wall superheats at the minimum heat flux on aluminum and 303E stainless steel hemisphere were 125 K and 145 K , respectively (El-Genk and Gao [15]). The reason for the wall superheat difference between aluminum and 303E stainless steel was difference in the thermal properties of the test sections. As the thermal diffusivity of aluminum is similar to that of copper, the thermal conductivity considerably affects the wall superheat and the minimum heat flux. From our experimental results and El-Genk and Gao [15] s, the high thermal conductivity results in the lower wall superheat and the minimum heat flux. However, the maximum heat flux in our experiment is about 100 kW/m^2 which is lower than the maximum heat flux values presented by Cheung et al. [16] and El-Genk and Gao [15]. This is because the thermal conduction heat transfer is ignored in this study. Bi exceeds 0.1 at the maximum heat flux. When the thermal conduction heat transfer is taken into account, the maximum heat flux calculated from our experiment will tend to approach the general critical heat flux.

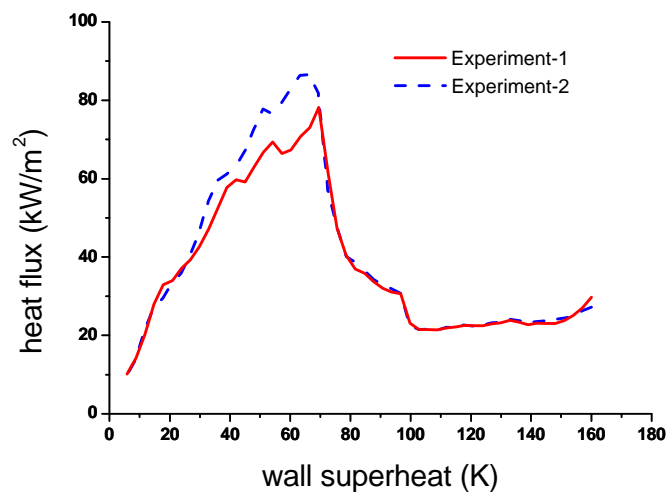
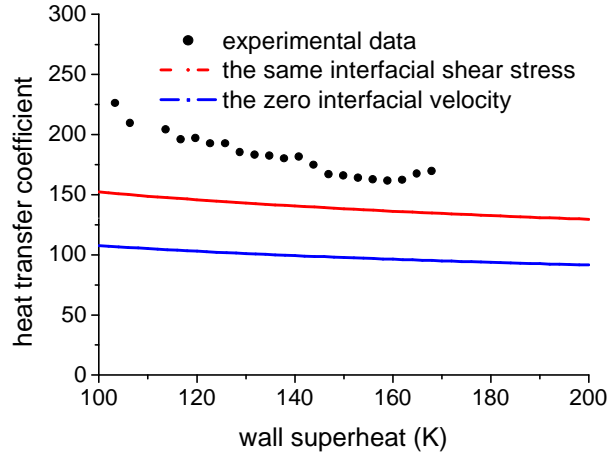


Figure 4 Boiling Curve

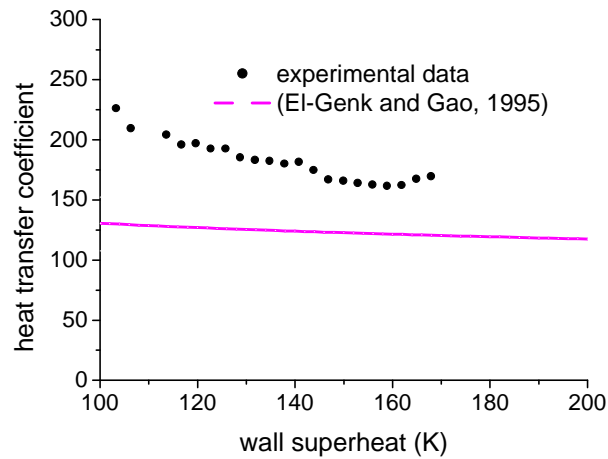
Figure 5(a) illustrates the film boiling heat transfer coefficients with the wall superheat from the experiment and the numerical analysis. The heat transfer coefficients from our experiments are larger than those from the numerical analysis for case 2. It shows that the film boiling on the relatively large diameter hemisphere is not simply laminar.

Figure 5(b) shows the film boiling heat transfer coefficients derived from the two experiments. The diameter of the test section in our experiments is the same as the curvature diameter of the test section in El-Genk and Glebov [17]. The material of the two test sections is identical, i.e. copper. The film boiling heat transfer coefficient values from our experiments are larger than those from El-Genk and Glebov [17] s experiments. The large edge angle

increases the vapor removal in the edge. Hence, the large edge angle increases the film boiling heat transfer coefficients.



(a) Experiment vs Numerical Analysis



(b) Comparison with a Different Experiment

Figure 5 Film Boiling Heat Transfer Coefficient

Hsu and Westwater [18] estimated the condition for the onset of transition to turbulent flow in film boiling as

$$Re_d = \frac{r_v du_d}{m_v} = 100$$

where u_d is the local vapor u-velocity at the interface and Re_d is the vapor film Reynolds number. With increasing the angle above the film thickness continues to increase, the vapor flow becomes more fully turbulent, and the interfacial waves increase in

wavelength, eventually becoming unstable. When this occurs the interfacial waves may roll up and “break,” releasing vapor bubbles into the adjacent liquid.

Figure 6 shows the vapor film Re_d in the same condition as this experiment. The larger wall superheat makes the smaller transition angle when the vapor film Re_d is 100. Especially, the laminar film boiling region covers the most part of the downward-facing hemisphere at the lower wall superheat. But, the experimental results are larger than the numerical analysis such as the high wall superheat. Turbulent film boiling is not important, because the vapor film Re_d is high enough to change laminar flow to turbulent flow. From Bui and Dhir [8] and Kolev [10], the interfacial wavy motion due to Helmholtz instability will be the main factor of underprediction by the laminar film boiling. The limit of the vapor film thickness by the Helmholtz instability will increase the film boiling heat transfer coefficient.

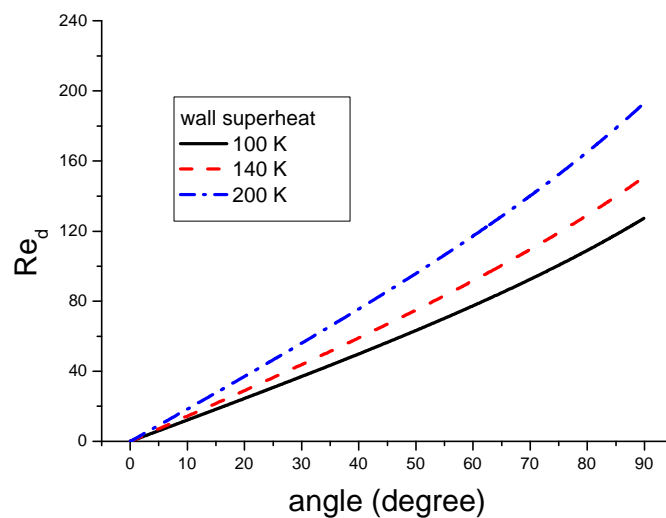


Figure 6 Vapor Film Re_d at the Same Condition as this Experiment

Figures 7, 8, 9 show the boiling mechanism in the film boiling, transition boiling, and nucleate boiling regions, respectively. In the film boiling, the thin vapor film covers all the outer surface of test section. In the transition boiling, the small bubbles are released from the outer surface with broken film. Finally, the relatively large bubbles are released from the outer surface in the nucleate boiling region.



Figure 7 Visualization of Film Boiling

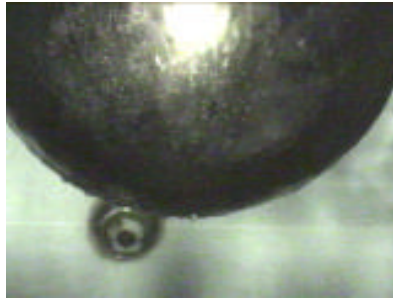


Figure 8 Visualization of Transition Boiling



Figure 9 Visualization of Nucleate Boiling

5. Conclusion

In this study, the film boiling heat transfer coefficients on the downward-facing hemisphere were obtained from the measured temperatures. The major results may be summarized as follows.

- (1) Higher thermal conductivity resulted in lower wall superheat and minimum heat flux.
- (2) The film boiling heat transfer coefficients in this study were larger than those given by the numerical solution for the laminar film boiling.
- (3) Large edge angle increased the film boiling heat transfer coefficients
- (4) Turbulent film boiling is not the governing mechanism which makes the film boiling heat transfer coefficient in this experiment

As follow-up to the present study, the new film boiling heat transfer coefficient correlation will be developed with the limit of vapor film thickness by Helmholtz instability. The effect of the test section diameter on the film boiling heat transfer will be experimentally investigated.

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