Study on Ex-Vessel Cooling of Reactor Pressure Vessel*

(Model Analysis of Critical Heat Flux on Inclined Plate and Hemisphere Facing Downward)

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Critical heat fluxes (CHF) on inclined plates and hemispheres in the case of saturated pool boiling were investigated analytically. In the present model, the most dangerous wavelength and propagation velocity in the Kelvin-Helmholtz instability on the liquid-vapor interface were calculated to determine the length and the velocity of the coalesced bubbles at CHF. The time period for which the coalesced bubble covered the heated surface was calculated as the length divided by the velocity. In close to the surface oriented downward, the characteristic length was provided by the length of the heater; the characteristic velocity was given by the correlation of the rising velocity of a spherical cap bubble with 17 to 40 mm the equivalent diameter. The predictions agreed well with previous experimental data obtained for an inclined plate in overall inclination angle. The model given as a function of the inclination angle was developed for the CHF on a hemisphere. The extended model well represented the experimental data on hemispheres.

Key Words: Heat Transfer, Boiling, Bubble, Critical Heat Flux, Model Analysis, Kelvin-Helmholtz Instability, Severe Accident

1. Introduction

The effects of surface orientation on pool boiling heat transfer and critical heat flux (CHF) have been of concern from the viewpoint of numerous industrial applications. In particular, the ex-vessel cooling of the reactor-pressure-vessel (RPV) in light-water-reactors has been proposed to maintain reactor vessel safety during a severe accident. The estimation of CHF from the underside of downward-facing convex surfaces, such as hemispheres, is important for the assessment of the cooling⁽¹⁾.

Numerous attempts have been made by investigators to examine the effects of the surface orientation on the pool boiling heat transfer and the critical heat flux. Howard and Mudawar⁽²⁾ examined CHF trigger mechanisms through experiments and visualizations, and proposed the CHF model based on Kelvin-Helmholtz instability for an inclined plate. Theofanous et al.⁽³⁾ reported the experimental data of CHF distribution on a hemispherical surface with a radius of 1.76 m and presented

the correlation of the CHF distribution on the hemispherical surface with the surface orientation. Furthermore, Theofanous et al.⁽⁴⁾ pointed out through numerical simulations that a vapor lens, i.e., a vapor dome, formed on the hemispherical surface was important for attaining CHF. Haddad and Cheung⁽⁵⁾ reported the experimental results on boiling heat transfer including the liquid-subcooling effects for a sphere with a radius of 0.152 m. Howard and Mudawar⁽⁶⁾ performed near-saturated pool boiling and flow visualization studies on a 90-degree slice of a downward-facing convex surface with a 3.2 mm width and 102.6 mm radius. They pointed out that the CHF commenced in the case of the most downward-facing surfaces, which have equivalent orientations of 0 to 20 degrees. They also found that individual bubbles nucleated, grew and coalesced together, forming a vapor blanket. A CHF correlation including large scale effects was also developed from SULTAN experiments⁽⁷⁾. It was pointed out in the report that under reactor conditions, the flow path would induce flow rates which were very different from the boundary layer flow rates associated with natural convection in a small open test section, thus the recirculation flow induced by this external flow path increased the CHF significantly.

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As a fundamental research on ex-vessel cooling of RPV, the authors⁽⁸⁾ experimentally examined CHF on inclined plates under saturated boiling conditions, focusing on the effect of the inclination angle on the CHF and the characteristic length and the characteristic velocity of a coalesced bubble near the heater at the CHF. The following conclusions were drawn. The critical heat flux increased with the inclination angle in the experimental range considered. The following correlation,

$$q_{CHF} = 0.0353 \theta^{0.33} \rho_v h_{fg} [\sigma(\rho_l - \rho_v)g/\rho_v^2]^{0.25} \quad (1)$$

was presented to provide the optimal agreement with the previous experimental results: the critical heat fluxes were proportional to the 0.33 power of the inclination angle in the experimental range considered. Furthermore, the CHF on the inclined plates under saturated boiling conditions were investigated analytically⁽⁹⁾ by using a macro-layer model⁽¹⁰⁾ and Kelvin-Helmholtz instability. In addition, the model was extended to the CHF on a hemispherical surface. The predictions of the CHF model agreed well with previous experimental data for CHF on inclined plates with 30 to 180 degrees inclination angles. The predicted CHF by the model, however, differed from the experimental results for inclination angle less than 15 degrees.

The purpose of this study is to examine the mechanisms of CHF on inclined plates and hemispheres, focusing on the effect of the inclination angle on the critical heat flux as a fundamental research on ex-vessel cooling of RPV. In this report, an analytical model of the critical heat flux on an inclined plate under saturated boiling conditions was modified for inclination angle less than 15 degrees. Then, the model was extended to the CHF on a hemispherical surface.

2. Experimental Apparatus

A schematic diagram of the experimental apparatus used in a previous study⁽⁸⁾ is shown in Fig. 1. Pool boiling experiments were performed for saturated R-113 liquid at 0.10 MPa.

The test section was fabricated from a coated copper film of 0.035 mm thickness on a plastic substance. The heater was 5 and 50 mm in width and length, respectively. The test section was heated by Joule heating of d.c. current supplied through electrodes from a low-voltage high-current stabilizer. The heating rate of the test section was determined from the supplied current and voltage between the voltage taps, where the distance between the taps was 40 mm. The wall heat flux was calculated using the heating rate and calibrated heat loss to the substance. The average temperature of the test section was obtained by referring to the measured electrical resistance calculated from the current and the voltage and the calibrated curve of temperature and electrical resistance expressed by a linear equation.

Fig. 1 Experimental apparatus⁽⁸⁾

The test bath was a commercial stainless steel bath. The test section arranged for several inclination angles was housed in the test bath. The angles from the horizontal downward-facing position were 0, 0.5, 1, 3, 5, 15, 30, 45, 90 and 180 degrees. In order to confirm the horizontal downward-facing position, the experiments for the inclination angles on the opposite side were also performed in the range of 0.5 to 5 degrees, namely -0.5 , -1 , -3 and -5 degrees.

The test section was submerged by pouring subcooled R-113 into the bath. Meanwhile, by adjusting the heating power to the bulk liquid and cooling flow rate into the condenser, a saturated state at $p = 0.10$ MPa was established. After the saturation condition was obtained, the d.c. current to the test section was increased stepwise, maintaining the single-phase natural convection to the nucleate boiling. The critical heat flux was determined as that immediately before the heating surface physically burned-out. The behavior of coalesced bubbles during the experiments was recorded on a system with a CCD video camera.

3. Analytical Model

3.1 Outline of previous model

Figure 2⁽⁸⁾ depicts the changes in behavior of the coalesced bubbles on the heated surface near the critical heat flux observed for a flat inclined surface. Individual bubbles grew and coalesced together, forming a vapor layer with wavy liquid-vapor interface similar to a vapor film of film boiling. Based on such observation results, the vapor-film-unit model⁽¹¹⁾ for saturated film boiling with wave motion along an inclined surface was developed for the CHF on an inclined plate in our previous study⁽⁹⁾. In the previous model, Kelvin-Helmholtz instability wavelength was used to determine the length scale of the vapor layer on the heater. In the model, wavelength and propagation velocity of the most dangerous wave in the Kelvin-

Fig. 2 Behavior of coalesced bubbles⁽⁸⁾

Helmholtz instability for an ideal fluid with vapor flow of finite thickness and surface tension at the liquid-vapor interface were calculated to determine the length and the velocity of the coalesced bubbles on the heated surface at CHF. The time period for which the coalesced bubble covered the heated surface was estimated as the calculated value with the length divided by the velocity. Finally, the CHF was predicted using the macrolayer model⁽¹⁰⁾ and the characteristic time.

3.2 Determination of characteristic length

The following assumptions are made for determining the characteristic length. The length of a vapor layer, which is the length of a coalesced bubble, is given by the most dangerous wavelength of the Kelvin-Helmholtz instability, $\lambda_{d,K-H}$. The wavelength is determined by a stability analysis for the interface with vapor flow and stagnant liquid. As far as the wavelength is concerned, both fluids are treated as incompressible and non viscous. The effect of evaporation at the interface on the stability is negligible. The time-averaged thickness and velocity of vapor flow, δ_v and U_v , do not depend on the distance from the leading edge of plate, x .

Considering the vapor-liquid interface along an inclined flat-plate in a gravitational field and analyzing the stability of the interface for the two-dimensional perturbation, results in the following equation:

$$\rho_l c^2 + \rho_v (c - U_v)^2 (1/m\delta_v) = \sigma m + (\rho_l - \rho_v) g \cos \theta / m. \quad (2)$$

Here, velocity of liquid U_l , thickness of liquid δ_l and thickness of the vapor layer δ_v are considered to be as follows:

$$U_l = 0, \quad \delta_l = \text{infinity}, \quad m\delta_v \ll 1$$

Under this condition, the wave number at which the growth rate is maximum, m_d , is given by the following equation,

$$m_d^4 + \frac{7\rho_v}{3\rho_l\sigma_v} + m_d^3 + \left(\frac{4\rho_v^2}{3\rho_l^2\delta_v^2} - \frac{\rho_v U_v^2}{3\sigma\delta_v} + \frac{\rho_v(\rho_l - \rho_v)g\cos\theta}{3\sigma} \right) m_d^2$$

$$- \left(\frac{\rho_v^2 U_v^2}{\sigma\rho_l\delta_v^2} + \frac{\rho_v(\rho_l - \rho_v)g\cos\theta}{\rho_l\sigma\delta_v} \right) m_d + \frac{2\rho_v^2(\rho_l - \rho_v)g\cos\theta}{3\rho_l^3\sigma\delta_v^2} = 0 \quad (3)$$

3.3 Determination of flow quantities

The δ_v and U_v are given from analytical results reported by Howard and Mudawar⁽²⁾. The equations by the analytical model in which the axial vapor momentum gradient is neglected, are as follows:

$$U_v = \bar{u}_v = \left[\left(\frac{\rho_l - \rho_v}{\rho_v} \right) g \sin \theta \frac{q \cdot x}{0.5 f_i \rho_v h_{fg}} \right]^{1/3}, \quad (4)$$

$$\delta_v = \frac{q}{\rho_v h_{fg}} \left[\left(\frac{\rho_l - \rho_v}{\rho_v} \right) g \sin \theta \frac{q \cdot x}{0.5 f_i \rho_v h_{fg}} \right]^{-1/3} x^{2/3} \quad (5)$$

where f_i in Eqs. (4) and (5) is selected as 0.5, as recommended by Howard and Mudawar⁽²⁾. The time-averaged thickness of the vapor layer is estimated as that at $x = \lambda_{d,K-H}$: the time-averaged velocity over the vapor layer is given as the averaged vapor velocity at this point, because Nishio and Ohtake⁽¹¹⁾ pointed out that the predictions made using $x = \lambda_{d,K-H}$ were in good agreement with experimental data of film boiling with wavy liquid-vapor interface.

3.4 Macrolayer model

The macrolayer model presented by Haramura-Katto⁽¹⁰⁾ is applied to the CHF on the downward-facing inclined plate, focusing on the characteristic length and the characteristic velocity on a coalesced bubble near the heated surface. The CHF on a horizontal upward-facing plate in pool boiling by the macrolayer theory is obtained by

$$\tau_d q_{CHF} A_w = \rho_l \delta_{macro} (A_w - A_v) h_{fg}. \quad (6)$$

Here, τ_d is the hovering time of a coalesced vapor bubble, A_w , the total heating area, δ_{macro} , the thickness of the macrolayer on the heated surface, and A_v , the total area of vapor stems on the heated surface. The δ_{macro} is based on Kelvin-Helmholtz instability in a thin liquid film on the heated surface. The instability is associated with counter-current flow between vapor leaving the wall and liquid

trying to flow towards the wall in a thin liquid film. Thus, for the model of CHF on an inclined plate, the δ_{macro} is also estimated by the following equation, which is proposed by Haramura and Katto⁽¹⁰⁾ for a horizontal plate:

$$\delta_{\text{macro}} = \frac{\lambda_H}{4} = \frac{\pi}{2} \sigma \frac{\rho_l + \rho_v}{\rho_l \rho_v} \left(\frac{A_v}{A_w} \right)^2 \left(\frac{\rho_v h_{fg}}{q} \right)^2. \quad (7)$$

The ratio A_v/A_w is given by

$$A_v/A_w = 0.0584(\rho_v/\rho_l)^{0.2}, \quad (8)$$

which is also recommended by Haramura and Katto⁽¹⁰⁾.

In the model, τ_d is the time period for which the coalesced bubble covers the heated surface. Namely, $\tau_{d,K-H}$ is given as the calculated value obtained by dividing the length of the coalesced bubble, $\lambda_{d,K-H}$, by the moving velocity of the bubble, c :

$$\tau_{d,K-H} = \lambda_{d,K-H}/c. \quad (9)$$

The moving velocity of the bubble, c , is estimated as the propagation velocity of the most dangerous wavelength for the Kelvin-Helmholtz instability. Therefore, c is calculated by the imaginary part of the imaginary solution of the second-order equation for c by rearranging Eq. (3):

$$c = \sqrt{\frac{\rho_l(\rho_v/m_d\delta_v)}{\{\rho_l + (\rho_v/m_d\delta_v)\}^2} U_v^2 - \frac{\sigma m_d}{\rho_l + (\rho_v/m_d\delta_v)} - \frac{(\rho_l - \rho_v)g \cos \theta}{\{\rho_l + (\rho_v/m_d\delta_v)\} m_d}}. \quad (10)$$

Near the upward-facing surface, Rayleigh-Taylor instability has a more dominant effect than the Kelvin-Helmholtz instability on the behavior of the coalesced bubble. Thus, the following τ_d is also considered in the present model:

$$\tau_{d,R-T} = \left(\frac{3}{4\pi} \right)^{1/5} \left(\frac{4\{(11/16)\rho_l + \rho_v\}}{g \cos \theta (\rho_l - \rho_v)} \right)^{3/5} \left(\frac{\lambda_{D,R-T}^2 q}{\rho_v h_{fg}} \right)^{1/5}. \quad (11)$$

The gravitational acceleration in the equation presented in Ref. (10) is replaced by $g(\cos \theta)$ because of the gravitational term modification for the inclined plate. Finally, τ_d is given by the following equation for each inclination angle:

$$\tau_d = \min(\tau_{d,K-H}, \tau_{d,R-T}). \quad (12)$$

3.5 Modified model

As reported in a previous paper⁽⁹⁾, below an inclination angle of 15 degrees, the Kelvin-Helmholtz instability did not occur in the previous model since the effects of the gravity and the surface tension on the stability of the interface were stronger than the effect of flow on the instability. Therefore, the predicted CHF's by the model differed from the previous experimental results⁽⁸⁾ for inclination angle less than 15 degrees.

In the present modified model, the characteristic length of a coalesced bubble is given by the length of the heater below the vapor flow for an inclination angle of 0 to 15 degrees from the horizontal downward-facing position: the length is 50 mm in the present case. The characteristic velocity of the coalesced bubble is estimated from the correlation for the rising velocity of a spherical cap bubble with 17 to 40 mm the equivalent diameter (D_e : the diameter the bubble would have if it were spherical)⁽¹²⁾:

$$u_b = 0.71[gD_e(\rho_l - \rho_v)/\rho_l]. \quad (13)$$

In the modified model, g in Eq. (13) is replaced by $g(\sin \theta)$.

Fig. 3 Effect of bubble length and bubble velocity on inclination angle

The time period for which the coalesced bubble covers the heated surface, $\tau_{d,\theta < 15}$, is also given as the calculated value with the characteristic length divided by the characteristic velocity:

$$\tau_{d,\theta < 15} = 50 \times 10^{-3} / u_b. \quad (14)$$

4. Calculated Results and Discussion

4.1 CHF on inclined plate

In Fig. 3, the predicted values of the most dangerous wavelength of the Kelvin-Helmholtz instability, $\lambda_{d,K-H}$, by Eq. (3) are compared with the observed results for characteristic length of the coalesced bubbles (see L in Fig. 2(c)) in our previous report⁽⁸⁾ against the inclination angle. As shown in Fig. 3, the predicted values of $\lambda_{d,K-H}$ agree with the observed results qualitatively except for an inclination angle less than 15 degrees. As mentioned in Sect. 3.5, the liquid-vapor interface was stable at an inclination angle of less than 15 degrees. For an inclination angle of less than

Fig. 4 Time period covered over the heating surface with coalesced bubble

15 degrees, the experimental data of characteristic length near the horizontal downward-facing position is close to 50 mm.

The propagation velocities of the most dangerous wavelength of the Kelvin-Helmholtz instability, c , calculated by Eq. (10) are also plotted with observed values for moving velocities of the coalesced bubbles⁽⁸⁾ in Fig. 3. There is a discontinuous point at 15°, however, the predicted velocities are also qualitatively similar to the observed results.

The values of time period calculated by Eq. (9) with $\lambda_{d,K-H}$ and c are shown with the observation period of the coalesced bubbles covering the heater⁽⁸⁾ in Fig. 4. The values calculated by Eq. (14) are plotted for inclination angles less than 15 degrees in Fig. 4. Although a discontinuous point at 15° appears on the calculated curve, the calculated values of the time period also agree with the observed results qualitatively.

In Fig. 5, the predicted values of the CHF calculated by Eqs. (6) to (14) are plotted against the inclination angle for R-113 and water. In this figure, the experimental results reported in our previous paper⁽⁸⁾, and those by Howard and Mudawar⁽²⁾ and Guo and El-Genk⁽¹³⁾ are shown for comparison. The experimental data for saturated water obtained by Bui and Dhir⁽¹⁴⁾ and the Toshiba group⁽¹⁵⁾ are also included in Fig. 5. The experimental data reported by Howard and Mudawar⁽²⁾ were obtained by using FC-72 liquid. The experimental data reported by Guo and El-Genk⁽¹³⁾ were obtained by quenching in the case of saturated water. The prediction by the present CHF model agrees well with the experimental data of CHF in overall inclination angle for organic liquid^{(2),(8)}, as shown in Fig. 5. The prediction by the present CHF model for water, which is plotted by the dashed line in Fig. 5, is close to the data reported by Guo and El-Genk⁽¹³⁾. In the present simulation, the Rayleigh-Taylor instability has a more dominant effect on the characteristic time than the Kelvin-Helmholtz instability when the inclination angle is

Fig. 5 Dependence of surface orientation on CHF

Fig. 6 Extension to hemisphere with large diameter

more than 135 degrees.

4.2 Extension to hemispherical surface

In the following section, the present model described in the previous section is extended to CHF on hemispherical surfaces of large and medium-size diameters. The present model given as a function of the inclination angle relative to the horizontal downward-facing plate is developed for the CHF on a hemispherical surface.

Regarding a hemisphere with large diameter, it is postulated that the local CHF at each position along the hemisphere is estimated similar to that for an inclined plate with equivalent orientation, $q_{CHF,IP}[\theta]$ as shown in Fig. 6. As an example of the experimental condition reported by Theofanous et al.⁽³⁾, the length of the arc along the hemisphere per 1 degree is 30.7 mm on a hemispherical heater with a radius of 1.76 m. Thus, the local CHF at θ on the hemisphere is given by:

$$q_{CHF,Hemisphere}[\theta] = q_{CHF,IP}[\theta] \quad \text{for large diameters.} \quad (15)$$

On the other hand, the length of the arc along the hemisphere per 1 degree is 2.6 mm for the hemispherical heater with a radius of 152 mm⁽⁵⁾. The arc is 1.8 mm per degree for a convex surface with $R = 102.6$ mm as reported by Howard and Mudawar⁽⁶⁾. Therefore, as shown in Fig. 7, the local CHF at each position along the hemisphere of medium-size diameter is estimated as the area-averaged local CHF from the horizontal downward-facing position 0 to a prescribed angle θ :

$$q_{CHF,Hemisphere}[\theta] = \int_0^\theta q_{CHF,IP}[\theta] \cdot 2\pi R^2 \sin\theta d\theta \bigg/ \int_0^\theta 2\pi R^2 \sin\theta d\theta$$

Fig. 7 Extension to hemisphere with medium-size diameter

Fig. 8 Development to hemispherical surface

$$= \int_0^{\theta} q_{CHF,IP}[\theta] \cdot 2\pi R^2 \sin\theta d\theta / (\cos\theta - 1) \quad (16)$$

For the present model, the characteristic length in τ_d is substituted for the arc disappeared for which the instability from 0 to 15 degrees: the length was $R \times 15^\circ \times \pi/180$.

In Fig. 8, the predicted value of CHF for the hemispherical heater of large diameter by Eq. (15) is plotted against inclination angle by a curved solid line for water and a curved dot line for R-113. The CHFs calculated by Eq. (16) for the hemisphere with medium-size diameter are represented by two horizontal dashed lines for an organic liquid. In this figure, the experimental results reported by Theofanous et al.⁽³⁾, Haddad and Cheung⁽⁵⁾ and Howard and Mudawar⁽⁶⁾ are shown for comparison. The prediction by the correlation presented by Guo and El-Genk⁽¹³⁾ for saturated water is also shown in Fig. 8. The CHF data presented by Theofanous et al.⁽³⁾ were conducted by using a downward-facing hemispherical surface with a radius of 1.76 m. Those by Haddad and Cheung⁽⁵⁾ were obtained for a hemispherical heater with a radius of 0.153 m. The CHF data obtained by Howard and Mudawar⁽⁶⁾ were for a convex surface with a radius of 0.1026 mm. As seen from Fig. 8, the prediction of CHF for the hemisphere of large diameter by Eq. (15) describes well the experimental results⁽³⁾ both qualitatively and quantitatively. In the hemisphere with medium-size diameter, the predicted CHF values by Eq. (16) are also

in good agreement with the experimental data for an organic liquid⁽⁶⁾ both qualitatively and quantitatively. On the other hand, the present CHF model of a hemisphere with medium-size diameter overestimates the experimental data for water⁽⁵⁾. For inclination angles of approximately 70 to 80 degrees for which the hottest surface temperature of the vessel is anticipated, the expected cooling rate is approximately 0.8 MW/m² as seen from Fig. 5.

Although future examination is necessary to estimate the characteristic length and the characteristic velocity, the present CHF model concurs well with the experimental results.

5. Conclusions

As a fundamental study on the ex-vessel cooling of a reactor-pressure-vessel, the critical heat fluxes on the inclined plates in the case of saturated pool boiling were investigated analytically by modifying our previous model. Furthermore, the present model given as a function of the inclination angle relative to the horizontal downward plate was extended to the CHF on a hemispherical surface. The following conclusions were obtained.

(1) The predictions made for the present CHF model by using the macrolayer model agreed well with previous experimental data for CHF on inclined plates in overall inclination angle. For inclination angle of 15 to 180 degrees, the characteristic length and the characteristic velocity of a coalesced bubble were estimated by Kelvin-Helmholtz instability. On the other hand, for inclination angle of 0 to 15 degrees, the characteristic length was given by the length of the heater and the characteristic velocity was given by the correlation for rising velocity of a spherical cap bubble with 17 to 40 mm the equivalent diameter.

(2) The prediction of CHF for a hemisphere with large diameter by the present local-CHF model described well the experimental results both qualitatively and quantitatively. For the hemisphere with medium-size diameter, the predicted CHF by the present area-averaged local-CHF model was also in good agreement with the experimental data for an organic liquid both qualitatively and quantitatively; the present CHF model concurred with the experimental data for water, qualitatively.

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