Film flow on a wall and critical heat flux

Yasuo KOIZUMI*
* Shinshu University
3-15-1 Tokida, Ueda City, Nagano 386-8567, Japan
E-mail: koizumi@shinshu-u.ac.jp

Received 17 October 2013

Abstract
Since there were large waves on the film, the minimum wetting rate (MWR) was greatly affected by the waves. The contact angle of the film at the top edge of the stable dry-patch varied periodically synchronizing with the arrival of the waves. When the contact angle exceeded the maximum advancing contact angle, the top edge of the dry-patch began to move downward, i.e. the rewetting of the dry-patch was initiated. The MWR was properly given by considering the force balance at the top edge of the dry-patch that when the maximum of the dynamic pressure of the film fluctuating according to the waves exceeds the film holding force by surface tension corresponding to the maximum advancing contact angle. Many tiny bubbles were observed in the film in the falling film boiling and the upward flow boiling. The bubble generation in the film might create a dry-patch locally in the film. If the film flow coming to the dry-patch could not rewet it, the CHF condition occurred. In the falling film boiling, since the long film flow might have a larger disturbance of the film flow than the short film flow, the CHF of the long falling film boiling was higher than the CHF of the short falling film boiling. The disturbance of the film flow of upward flow boiling was larger than that of the falling film boiling. Thus, the CHF of the upward flow boiling was larger than the CHF of the falling film boiling. The CHF of those were predicted with a unique correlation except for the constant that expressed the difference of the degree of the disturbance of the film flow. The CHF of the flat mini-channels were also predicted well with the CHF correlation except for the constant. The constant, i.e. the CHF, was lower than that of the CHF of the falling film boiling. Since a wall effect due to the viscosity that suppressed the growth of the film flow disturbance was enhanced in the flat mini-channels, the CHF might become smaller. Correlations for the wavelength, the maximum film thickness and the wave velocity were introduced. The proposed correlations required only a film flow rate, physical parameters and geometrical dimensions. These values of the wave characteristics were required in the correlations of the MWR and the CHF. What is left toward the next step is to incorporate these characteristics of the waves with the MWR and CHF correlations.

Keywords: Film flow, Minimum wetting rate, Contact angle, Waves, Dry patch, Dry-out, Critical heat flux

1. Introduction
Film flow on a wall is quite usual in many industry processes and chemical plants. For example, the falling film plays the important part of a wetted wall tower that is used for distillation of crude oil. When the film falls down on the heated wall, the wall is kept at low temperature while the wall is covered with the film. Once the film breakup occurs and a dry area is formed on the wall, the wall temperature goes up very high. Therefore, the film breakup sometimes leads to the operating limit of facilities. Careful attention should be paid to the film breakup in designing or operating the facilities.

It has been reported that the occurrence of the critical heat flux (CHF) condition in the falling film boiling is closely connected with the film breakup (Ueda et. al., 1981a). The condition of the film breakup is affected by the film flow rate and the heat flux. In forced flow boiling and evaporation in a heated tube such as a boiler tube, it is sometimes
assumed that when the film flow rate on the tube wall disappears, the CHF condition occurs. However, the occurrence of film breakup or the appearance of the dry area in the film flow before the disappearance of the film flow actually leads to the initiation of tube wall temperature excursion, i.e. the CHF condition.

The behavior of the film flow and the CHF is closely related each other as stated above. Thus, researches for the film flow have a long history. Outcomes have been reported by many pioneers such as Hewitt and Hall-Taylor (1970) and Ueda (1981c). The author of this paper has had interest in the relation of the film flow behavior and the occurrence of the CHF condition and performed researches following many pioneers. Results of

1. Minimum wetting rate
2. Critical heat flux of film flow
3. Critical heat flux of mini channel
4. Characteristics of falling film flow

by the author will be presented in the present paper as review in this research area.

2. Minimum wetting rate

The breakup of the adiabatic film, the evaporating or boiling film and the condensing film have been investigated in the past by many investigators as reviewed by Hewitt and Hall-Taylor (1970) and Ueda (1981c). When the flow rate of the film flowing down on the isothermal wall is decreased, the film flow reaches eventually a limiting state that dry-patches generated on the wall can exist stably or the film disrupts into rivulets. The minimum film flow rate at which the liquid film can flow on the wall as a continuous film is called the minimum wetting rate (MWR).

Hartley and Murgatroyd (1964) supposed that the dynamic pressure of the film was necessary to balance with the upward component of the surface tension at the front edge of the permanent dry-patch, and then derived the MWR from the limiting situation to sustain the dry-patch. On the other hand, Hartley and Murgatroyd (1964) and Bankoff (1971) considered the total energy of the film flow that was the sum of the kinematic energy and the surface energy, and then proposed a correlation for the MWR. However, the MWRs calculated with those methods are considerably larger than measured results. Ueda have pointed out that the assumption of the smooth surface film may be related to the over-prediction. Since there exist many waves on the film and the dynamic pressure of the film fluctuates, the maximum value of the fluctuating dynamic pressure seems appropriate to be considered for the film breakup or the rewetting.

Koizumi et al. (1999) examined the MWR of the isothermal water film flowing down on the outer surface of pipes arranged vertically considering the importance of the relation between the MWR and the waves on the film surface.

2.1 Analytical model of MWR

Hartley and Murgatroyd (1964) proposed the MWR $\Gamma_c$ correlation by assuming that the critical film thickness below which the film disrupts is given by the condition that the sum of the surface and the kinematic energy becomes minimum;

$$\Gamma_c = 0.803 \sigma^{1/3} (\mu \rho / g)^{1/5}, \quad (1)$$

where $g$ denotes the gravitational acceleration, $\mu$ the liquid viscosity, $\rho$ the liquid density and $\sigma$ the surface tension.

Hartley and Murgatroyd also presented the MWR correlation by considering the force balance at the stagnation point of the film as shown in Fig. 1. At the stagnation point of the film, the dynamic pressure $\Delta P_f$ of the film flow needs to balance with the upward component of the surface tension ($\sigma (1 - \cos \theta)$). If the dynamic pressure overcomes the surface tension term, the stagnation point is initiated to move downward and the dry-patch is rewetted. They assumed the smooth surface film. Then, the force balance at the front edge of the dry-patch is,

$$\Delta P_f = \sigma (1 - \cos \theta) \quad (2)$$

and
\[ \Delta P_f = \frac{1}{2} \int_0^{y_i} \rho u^2 \, dy. \]  \hspace{1cm} (3)

In this equation, \( y \) is the coordinate normal to the wall surface, \( y_i \) is the film thickness and \( u \) is the downward liquid velocity at \( y \). If the laminar film is assumed, the shear stress is \( \tau = \mu \frac{du}{dy} = \rho g (y_i - y) \). Then, it is integrated to

\[ u = \frac{\rho g}{\mu} \left( y_i y - \frac{1}{2} y^2 \right). \]  \hspace{1cm} (4)

From this equation, the film flow rate per unit width \( \Gamma \) is derived as

\[ \Gamma = \int_0^y \rho u \, dy = \frac{\rho^2 g}{3} \mu y_i^3. \]  \hspace{1cm} (5)

And also using Eq. (4), Eq. (3) comes to

\[ \Delta P_f = \frac{1}{15} \frac{\rho^3 g^2}{\mu^2} y_i^5. \]  \hspace{1cm} (6)

Thus, from Eqs. (2), (5) and (6), the MWR based on the force balance at the stagnation point is expressed as the film flow rate per unit width;

\[ \Gamma_c = 1.69 \left[ \sigma (1 - \cos \theta) \right]^{3/5} \left( \frac{\mu \rho}{g} \right)^{1/5}. \]  \hspace{1cm} (7)

Fig. 1 State of Stagnation Point of Film at Front Edge of Dry-Patch (Koizumi et al., 1999)
2.2 Measurement of MWR, Contact angle and wave characteristics

Koizumi et al. (1999) measured the MWR by using the test facility shown schematically in Fig. 2. Deionized water was used in experiments. The experiments were performed at room temperature. Water pumped out from a storage tank flows down through a sintered metal as a uniform falling film on the outer surface of the test pipe arranged vertically. The test pipe was covered with a Plexiglas pipe of 50 mm ID and 1.65 m long concentrically to prevent the falling film from being disturbed by the ambient air. On the cover pipe, a slit of 35 mm wide and 1.65 m long was cut for an operation to cause the artificial film breakup.

The MWR was measured following the method of Hewitt and Lacey (1965). A small air jet was blown perpendicularly to the film for a short time period from a syringe to form a dry-patch in the film artificially. Then it was closely watched whether the dry-patch was rewetted by the film or not. When the dry-patch was erased out, the film flow rate was decreased little and the same procedure was iterated to reach the limiting state that the dry-patch could exist stably. By this procedure, the minimum film flow rate at which the dry-patch was rewetted by the film, i.e. the MWR, was determined.

In addition to the above measurements of the MWR, the film flow rate at which the rewetting of the dry-patch was initiated was examined by increasing a flow rate from the condition that the stable dry-patch was in existence. Besides, the film flow rate was decreased stepwise little by little from the state that the pipe wall was covered with a continuous-uniform film. Then, the film flow rate at which the film broke up spontaneously was also measured. Four test pipes were used; Plexiglas pipes of 25.0 mm OD and 1.7 m long, 10.0 mm OD and 1.0 m long, 6.0 mm OD and 1.0 m long and a stainless steel pipe of 25.0 mm OD and 1.7 m long. In the case of the stainless steel pipe, the surface was polished with #180, 600 or 1200 emery paper.

The contact angle of the film at the top of the dry-patch was also measured. In that experiments, the stainless steel pipe of 25.0 mm OD polished with #600 emery paper was used as the test section. First, a dry-patch was formed in the film by the procedure stated above. Then, sheet-type flash-light was projected toward the axis of the pipe and the pictures of the front edge of the dry-patch were taken perpendicularly to the light sheet for two minutes with a video camera. The contact angle was determined from the recorded pictures.

The characteristics of large waves on the film were also examined. The test section used was the stainless steel pipe of 25.0 mm OD polished with #600 emery paper. The side view of waves on the film was recorded for two minutes with a video camera. The maximum film thickness (the distance from the pipe surface to the crest of the large wave) and the minimum film thickness (the distance from the pipe surface to the trough between the large waves) were derived. The velocity of the large waves was deduced from the traveling distance and the elapsed time. The electric capacitance method was used to measure the wave frequency. The variation of the electric capacitance between the electric capacitance probe and the pipe surface on which the film flowed down was detected with 500 Hz to obtain the frequency of the large waves.

Fig. 2 Experimental Apparatus for MWR Measurement (Koizumi et al., 1999)
2.3 Results

Minimum wetting rates (MWRs) measured are plotted in Figs. 3 through 5 against the axial distance X from the top of the falling film. It is shown in each figure that the MWR decreases steeply with the distance X and reaches a nearly constant value after X = 0.6 m.

As the surface of the stainless steel pipe becomes smooth, the MWR tends to become low a little in Fig. 4. However, the difference in the value of the MWR is very small. The dashed line in the figure represents the MWR of the Plexiglas pipe of diameter D = 25.0 mm; the mean value at each elevation. The MWRs of the stainless steel pipes are slightly smaller than those of the Plexiglas pipe.

Under the condition that the stable dry-patch was formed first, the film flow rate was increased stepwise again, and the film flow rates at which the dry-patch was rewetted was determined. The flow rate obtained by this procedure were almost the same as the MWRs as shown in Fig. 5.

By using the stainless steel pipe finished with #600 emery paper, the film flow rate was gradually decreased little by little stepwise. The film broke up spontaneously at a flow rate of $\Gamma = 5.0 \times 10^{-3}$ kg/ms. This value is much smaller than the aforementioned MWR. The position where this spontaneous breakup commenced was not fixed. When the spontaneous breakup appeared, the dry-patch spread over the pipe surface through the top and the bottom, and the film broke into several rivulets. The film flow rate at the spontaneous film breakup occurrence was close to the value $\Gamma = 1.0 \times 10^{-2}$ kg/ms of Norman and McIntyre (1960) which was measured for the 30 ~ 75°C water film flowing down on the inner surface of a vertical copper pipe.

The value $\Gamma_c$ calculated by Eq. (1) is illustrated by a solid line in Figs. 3 and 4. The calculated MWR is considerably larger than the measured MWR except for the region close to the top of the test pipe where waves on the film are undeveloped. The idea of Hartley and Murgatroyd on which Eq. (1) is based seems to be rather suitable for the spontaneous disruption of the film resulting from the film flow rate decreasing. However, the film flow rate at the spontaneous film disruption in the experiments is $\Gamma = 5.0 \times 10^{-3}$ kg/ms as mentioned before and much smaller than the value of Eq. (1).

If it is assumed that Eq. (7) can predict the MWR $\Gamma_c$, the contact angle $\theta$ of the film at the top of the dry-patch can be calculated by adapting the measured $\Gamma_c$. The contact angles so derived are presented in Fig. 6. The calculated contact angles decrease steeply with the distance X and settle down at a low value.

Figure 7 shows the pictures of the dry-patch front taken for the same film flow rate. The pictures (a) and (b) correspond to the thickest and the thinnest film state, respectively. The state of the film at the stagnation point varied periodically between (a) and (b). The moving-down of the film stagnation point (the rewetting of the dry surface) was always initiated from the state (a). It is supposed that the states (a) and (b) correspond to the condition that the crest and the trough of the wave on the film has just arrived at the dry-patch front, respectively.

The contact angles $\theta$ that was measured at the top of the dry-patch while the dry-patch stably stayed there are plotted against the film Reynolds number $Re_f = 4\Gamma/\mu$ in Fig. 8. Solid symbols are for the maximum contact angle and open symbols are for the minimum contact angles. The contact angle fluctuated between these values. The arrow symbol indicates the MWR. In the case of X = 0.1 m, the picture of the film stagnation point could not be taken in the range of $0 > 90^\circ$ since the film around the front edge of the dry-patch-overshadowed the front portion of the dry-patch. The advancing and the receding contact angle of water measured by Katoh et al. (1995a and 1995b) are also included for comparison in the figure.

The minimum contact angle stays at low value irrespective of the film flow rate and the value is very close to the minimum value of Katoh et al.’s receding contact angle $\theta = 10^\circ$ in Fig. 8. The maximum value of the fluctuating contact angle increases rapidly with the film flow rate and reaches a critical value. The critical values, namely the maximum contact angles measured right before the moving-down of the stagnation point (the dry-patch rewetting), are approximately equal to the maximum advancing contact angle $\theta = 120^\circ$ obtained by Katoh et al. This tendency and the value itself are considerably different from Fig. 6.

Above results imply that the wave on the film is closely related with the MWR. The maximum and the minimum film thickness measured in the experiments are plotted for the axial distance X in Fig. 9. In Fig 10, these are also presented against the film Reynolds number $Re_f$. The solid line in Fig. 9 is the film thickness calculated with the Nusselt equation for a laminar film $y_m$ (g/\nu_l)^{2/3} = [(3/4)Re_f]^{1/3}$ where $y_m$ is the film thickness and $\nu_l$ is the kinematic viscosity of liquid. Figures 9 and 10 indicate that there exist waves with large amplitude on the film and the amplitude grows as the film flows down. The amplitude reaches up to ten times as large as the minimum film thickness in the...
experimental range. The amplitude ceases to grow after $X \geq 0.6$ m and becomes nearly constant thereafter. It is realized that the amplitude is greatly affected by the film flow rate; the higher the film flow rate is, the larger the amplitude is.

The MWR significantly depended on the distance X as shown in Figs. 3 ~ 5. The MWR decreased steeply with X and then approached to the nearly constant value in $X \geq 0.6$ m. This result seems to be connected with what is observed in Figs. 9 and 10. In the region close to the top of the falling film, the growth of waves is insufficient, the large flow rate is needed for rewetting of the dry-patch, and then the MWR is high. In the downstream region, the waves have grown to have large amplitude and the MWR becomes low.

The frequency and the velocity of the large waves greatly varied with X until $X \geq 0.6$ m and the variations of these became gentle after $X \geq 0.6$ m. It is considered that a certain length, approximately 0.6 m in the experiments, is required for the large waves to grow and thereafter the growth calms down.

![Fig. 3 Minimum Wetting Rates (Plexiglas Pipes) (Koizumi et al., 1999)](image1)

![Fig. 4 Minimum Wetting Rates (Stainless Steel Pipes) (Koizumi et al., 1999)](image2)
Fig. 5 Minimum Wetting Rates (The film flow rate was increased after the permanent dry-patch was formed.) (Koizumi et al., 1999)

Fig. 6 Contact Angles Predicted with Correlation of Hartley and Murgatroyd (1964) (Koizumi et al., 1999)
Fig. 7 Photos of Stagnation Point of Film (at X = 0.6 m, Re_f = 35) (Koizumi et al., 1999)

(a) Maximum Contact Angle State

(b) Minimum Contact Angle State

Fig. 8 Contact Angle at Front Edge of Dry-patch (Stainless steel pipe, D = 25 mm, Emery #600) (Koizumi et al., 1999)
Fig. 9 Film Thickness (Koizumi et al., 1999)

Fig. 10 Film Thickness (Koizumi et al., 1999)
2.4 Effect of waves on MWR

In the analysis of Hartley and Murgatroyd, the smooth surface film was assumed. However, there are many waves on the actual film as pointed out above. It was observed that when a large wave reached the front edge of the dry-patch, the stagnation point of the film hung over the dry-patch as shown in Fig. 7 (a) and then the contact angle exceeds 120° (the maximum advancing contact angle, Fig. 8), the rewetting of the dry-patch was initiated. Therefore, the maximum film thickness and the maximum advancing contact angle are appropriate to be considered as shown in Fig. 11.

At the critical film flow rate condition, the force balance at the front edge of the dry-patch should be expressed as

\[ \frac{1}{2} \rho \int_0^{y_{\text{imax}}} \rho u^2 \, dy = \sigma (1 - \cos \theta_{\text{max}}) \]  

(8)

Here, \( y_{\text{imax}} \) and \( \theta_{\text{max}} \) denote the maximum film thickness and the maximum advancing contact angle, respectively.

The left hand term of Eq. (8) represents the dynamic pressure of the film accompanied by a large wave. This value is presently difficult to predict directly. However, if the velocity profile in the film with a large wave is assumed to be similar to that in the smooth laminar film; Eq. (4), Eq. (8) may be reduced to

\[ \frac{1}{15} \frac{g^2}{\mu^2} y_{\text{imax}}^5 = \sigma (1 - \cos \theta_{\text{max}}) \]  

(9)

and using Eq. (6) the following relation is obtained.

\[ \left( \frac{y_{\text{imax}}}{y_i} \right)^5 = \frac{\sigma (1 - \cos \theta_{\text{max}})}{\Delta P_f} \]  

(10)

For the measured MWR \( \Gamma_c \), the imaginary-smooth surface film thickness \( y_i \) can be calculated from Eq. (5) and the dynamic pressure \( \Delta P_f \) of the film is determined by Eq. (6). The maximum film thickness \( y_{\text{imax}} \) was measured in the experiment and the measured maximum contact angle \( \theta_{\text{max}} \) was 120°. Therefore, the term of \( (y_{\text{imax}}/y_i)^5 \) and \( \sigma (1 - \cos \theta_{\text{max}})/\Delta P_f \) in Eq. (10) can be calculated for the experimental conditions. The calculated values are plotted in Fig. 12. The figure indicates that the relation between these terms is expressed fairly well by Eq. (10).

The above results explain the reason for the large discrepancy between the experimental results of the MWR and the analytical results of Hartley and Murgatroyd; the maximum advancing contact angle and the maximum film thickness are important in estimating the MWR. If the maximum contact angle \( \theta_{\text{max}} \) is given, that is 120° in the water film case, and the maximum film thickness \( y_{\text{imax}} \) of the wavy film is given, \( y_i \) is determined by using Eq. (6 ) and Eq. (10). Then, the MWR is predicted by using this \( y_i \) and Eq. (5).

In conclusion, it is highly recommended to examine the characteristics of waves on the film flow.

Fig. 11 Actual State of Stagnation Point of Film at Front Edge of Dry-Patch (Koizumi et al., 1999)
3. Critical heat flux of film flow

Let's consider the CHF of the falling film on the heated wall or the annular flow in a heated tube. It is tempting to consider that the film flow rate on the heated wall becomes zero to cause the CHF condition in these systems. However, the CHF condition is actually encountered before the film flow on the wall disappears. The film thickness is usually very thin in these systems and it has high heat transfer coefficient. Thus, boiling is rather suppressed in the film. Even so, boiling occurs in the film not extensively but limitedly when a heat flux becomes high.

When boiling occurs in the film system, a boiling bubble grows in the film, it becomes large and eventually it bursts as illustrated in Fig. 13. After the bubble bursts, a dry-patch is left in the film. Then, a large wave reaches to the top of the dry-patch. If the large wave can rewet the dry-patch, the wall is covered by the film again. If the wave cannot rewet the dry-patch, the dry-patch continues to exist there and wall temperature is initiated to rise up because of heat transfer deterioration. It may become the trigger of the CHF condition.

The process stated above is quite similar to the occurrence of the MWR. Considering it, Koizumi et al. (1994 and 1998) examined the CHF of the falling film system and the upward flow system by using R-113 as test fluid. The test section used is presented in Fig. 14. The flow channel arranged vertically was semicircular with 14.8 mm diameter. A circular arc side was a heated wall made of copper. The heated wall was heated by electric heaters fixed at an outer wall. A chordal side was made of transparent Pyrex glass. Thus, a flow state in the test channel could be observed through the Pyrex glass window.

Flow states observed in the falling film system and the upward flow system are presented in Figs. 15 and 16, respectively. In Fig. 15, the state (a) is at the CHF, where many tiny dry-patches which follow bubble nucleation are observed in the film. The tiny dry-patches disappear quickly, and then new dry-patches come out soon after. Near the exit end of the test section, small dry-patches appear and disappear repeatedly. At this point, no large heat-up of the heating surface is recorded. After a slight increase in the heat flux, the small dry-patches near the exit end spread out upstream in size as shown in Fig. 15 (b), and the intervals between the appearance and the disappearance are prolonged. At this stage, sharp rise or fluctuation in the surface temperature is noted.

The flow state at the CHF in the up-flow system is in Fig. 16 (a). The flow is an annular type. Small dry-patches appear and disappear repeatedly in the film near the exit end of the test section. At this point, no large heat-up of the heating surface is recorded. After a slight increase in the heat flux, stable dry-patches come out to cause the large heat-up of the heated wall as shown in (b).

Ueda et al. (1981a) classified the CHF condition of the falling film system into three types. The type I is mainly
observed in the experiments of a long heated test section. The film flow rate at the bottom exit decreases to a very low value with increasing heat flux, and then the CHF condition takes place by forming a large permanent dry-patch at the exit end of the heating test section. They presumed that the Type I CHF condition occurs when the exit film flow rate becomes less than the minimum wetting rate. Thus, the CHF condition does not depend on the heat flux. They assumed that the limiting value of the minimum wetting rate was 0.02 kg/ms from experimental results. It is interesting to note that this value is very close to the minimum wetting rate shown in Figs. 3 ~ 5. In the figures, the minimum wetting rate has stabilized around 0.015 ~ 0.020 kg/ms after the film flows down approximately 0.5 m.

In the Type II, the liquid film involving vapor bubbles was distorted around the tube periphery as the heat flux was increased, and large stable dry-patches that gave rise to the sharp rise in wall temperature was formed in a thinned film area.

In the Type III, there was a considerable amount of liquid flowing at the exit end. The film flowed down covering the tube periphery almost entirely. When the heat flux was increased near the CHF value, the main part of the film on the exit end of the heating section appeared to be separated from the heating surface. In this condition, a film disrupted area was formed in the film flow. This state was maintained until the heat flux was raised to the CHF.

Considering the discussion on the minimum wetting rate in the preceding section and Figs. 13, 15 and 16, it rather seems that the Type I corresponds to the minimum wetting rate by the spontaneous film breakup caused by film flow rate decrease. The Type III seems the state shown in Figs. 11 and 13. A bubble in the film bursts, a thin film under the bubble is dried, and the film disrupted area is left. When the film flow coming to the dried area cannot rewet it, the dry-patch stably exists there. When a tube is long and a heat flux is low, the film flow rate gradually decreases. The surface temperature uniformity is lost. The fluid temperature in the thin film area may become higher than that in the thick film area, which results in the surface tension gradient between the high temperature region and the low temperature region. As a result of it, liquid in the high temperature region, i.e. in the thin film region is pulled into the low temperature region, i.e. into the thick film region. The thickness in the thin/hot film region becomes thinner more and more to be dried eventually. It may cause the reason why the Type II appears. Thus, it seems that the Type II is the transition region from the Type III to the Type I. The boundary between the Type II and the Type III is not clear although Ueda et al. (1981a) presented the expression for the boundary. They pointed out that the Type III continued until the Type I region in some occasion.

The CHF of the Type III will be mainly discussed in the following. The CHF correlation for the Type II has been presented by Ueda et al. (1981a).

Katto and Ishii (1978) measured the CHF with a saturated liquid jet flowing over high heat flux surface of L = 0.01 ~ 0.02 m, and developed the following correlation

$$\frac{q_{cr}}{H_{fg}} = 0.0164 \left( \frac{\rho_g}{\rho_l} \right)^{0.133} \left( \frac{\rho_l u_e^2 L}{\sigma} \right)^{-0.33}$$

Considering it, Ueda et al. (1981a) defined the We = $\rho u_{mcr}^2 L_0/\sigma$ using the heating length $L_0$ and the mean film velocity $u_{mcr}$ at the CHF condition, and correlated the CHF data of the Type III by using the following correlation

$$\frac{q_{cr}}{H_{fg}} = 0.0135 \left( \frac{\rho_g}{\rho_l} \right)^{0.08} \left( \frac{\rho_l u_{mcr}^2 L_0}{\sigma} \right)^{-0.33}$$

Ueda et al. (1981b) also presented the CHF correlation for the upward flow in a vertical pipe

$$\frac{q_{cr}}{H_{fg}} = 0.060 \left( \frac{\rho_g}{\rho_l} \right)^{0.08} \left( \frac{\rho_l u_{mcr}^2 L_s}{\sigma} \right)^{-0.38}$$

Here, $L_s$ is the boiling length from the saturation point to the CHF condition location.

Equations (12) and (13) are compared with the CHF data of Koizumi et al. (1994 and 1998) in Fig. 17. In the
figure, the data of Ueda et al. (1981a and b) are also included for comparison.

As for the upward flow boiling, the mass flux is in the wide range of 2.7 ~ 1,700 kg/m²s. Nevertheless, all data plots in the figure are located near the extension of Eq. (13). When the mass flux becomes low, the vapor velocity at the CHF point also becomes low, which resulted in the thick film thickness at the CHF point. Actually, the film thickness at the CHF point is 0.09 ~ 0.3 mm in that mass flux range. It may be concluded that the bubble nucleation in the film create the dry-patch in the film that leads to the occurrence of the CHF condition.

The upward flow data in Fig. 17 extending over a wide range are well correlated by the following correlation

\[
\frac{q_{cr}}{H_{fg}} = 0.028 \left( \frac{\rho_g}{\rho_l} \right)^{0.08} \left( \frac{\rho_l u_{mcr}}{\sigma} \right)^{0.33} \frac{2L_s}{\sigma} \]  

(14)

The results of Koizumi et al. (1994 and 1998) of the falling film experiments show a trend quite similar to the CHF data of Ueda et al. (1981a and b) of the falling film system. Many tiny bubbles were observed in the falling film (Fig. 15). It is supposed that the bubble generation in the film created dry-patches locally to result in the CHF condition. Koizumi et al. data are expressed well by

\[
\frac{q_{cr}}{H_{fg}} = 0.0085 \left( \frac{\rho_g}{\rho_l} \right)^{0.08} \left( \frac{\rho_l u_{mcr}}{\sigma} \right)^{0.33} \frac{2L_s}{\sigma} \]  

(15)

In Fig. 17, the data points of Ueda et al. (1981a) are higher, approximately 1.8 times, than Koizumi et al. (1998). Disturbances of a film have an effect on suppressing the occurrence of dry-patches. The disturbance grows as the falling film proceeds downward as shown in Fig. 9. Thus, the film near the exit end of a pipe where the CHF condition is encountered is more disturbed in the case of Ueda et al. than in the case of Koizumi et al. since a longer test pipe was used in the experiments of Ueda et al. Therefore, it is suspected that the larger disturbance near the exit end of the test pipe resulted in the higher CHF in Ueda et al. than in Koizumi et al. (1999).

Figure 17 indicates that the CHF of the upward flow boiling are larger than those of the falling film boiling. The liquid film on the heated surface is propelled to flow upward against gravity by the interfacial shear stress imposed by vapor flow. Therefore, the ascending film is more disturbed than the falling film, and is rather fluctuating in a pulsative or oscillatory nature. Consequently, the occurrence of stable dry-patches in the film flow in the upward flow boiling system is considered to be suppressed, resulting in the higher CHF than in the falling film boiling as illustrated in Fig. 17.

The shape of Eqs. (14), (12) and (15) is the same except that the constants in the right-hand side of the equations; 0.028 for the upward flow boiling, 0.0135 for the long pipe falling film boiling and 0.0085 for the short pipe falling film boiling. It suggests that if the degree of disturbance of the film flow on the heated surface is known, the constant may be predicted from that aspect.

Fig. 13 Dry-Patch Formation in Film by Boiling Bubble
Fig. 14 Test Section for CHF Experiments (Koizumi et al., 1994)

Fig. 15 Flow State Observed in Falling Film System (Koizumi et al., 1998)
Fig. 16 Flow State Observed in Upward Flow System (Koizumi et al., 1994)

Fig. 17 Correlation of Dry-out Heat Flux of Falling Film and Upward Flow Boiling (Koizumi et al., 1998)
4. Critical heat flux of mini channel

In the former section, the CHF of the film flow was discussed. That idea may be applicable to many boiling systems.

Koizumi et al. (2001) examined the CHF of the forced flow boiling in vertical-narrow-annular passages. The test apparatus used in their experiments is presented in Fig. 18. The outer wall of the test section was made of copper. A glass pipe is inserted into the outer wall concentrically. The inner diameter of the outer wall was 34, 36 or 46 mm. The outer diameter of the glass pipe was 35, 32 or 26 mm. By combining those, the annular flow passages with the gap clearance of 0.5, 1.0, 2.0, 5.0 or 10.0 mm was created. The outer wall of the test flow channel was heated. A flow and a boiling state was observed and recorded with a fibrescope video camera through the transparent glass inner wall from the center side of the glass wall. The heating length was 220 mm. Test fluid was R-113.

The boiling condition followed the usual pool boiling relation such as the Rosenow (1952) pool boiling correlation. When the gap clearance was larger than 2.0 mm or a flow rate was large even in the case of the gap clearance of 1.0 and 0.5 mm, stable dry-patch appearance in the film on the heat transfer surface led to initiate heat transfer surface temperature excursion. Since data plots started to deviate from the relation of the Rosenow pool boiling correlation, the heat flux immediately before this point was selected as the CHF. When the gap clearance was smaller than 1.0 mm, the appearance of stable dry-patches did not result in the surface temperature excursion although it caused the deviation from the relation of the pool boiling. As the heat flux was further increased stepwise for a while, the surface temperature rose to settle down at a stable value without large heat-up at each step, and then the surface temperature excursion was eventually initiated after a several stepwise increase in the heat flux. The heat flux immediately before the initiation of the deviation from the pool boiling relation was defined as the CHF also in those cases.

The CHF data of Koizumi et al. (2001) are compared with Eq. (14) in Fig. 19. Interestingly enough, Eq. (14) predicted well the CHF except for the low mass flux case of the gap clearance of 0.5 and 1.0 mm. It is again confirmed that the occurrence of the CHF condition is closely related to the partial dry-out of the film caused by the bubble nucleation. When a bubble is generated in the film on the heat transfer surface and then it bursts, a thin film under the bubble is dried and a dry-patch is left behind on the heat transfer surface. If the film flow does not have enough momentum to rewet the partially dried area, the CHF condition comes around.

In Fig. 19, some data plots have deviated from the correlation in the low We number region. These are for the low mass flux cases of the narrow gap clearances of 0.5 and 1.0 mm. It seems that these are similar to the Type II of the falling film boiling discussed in Section 3. When the clearance is small and the flow rate is low, temperature difference may be created in the film once the dry-patch is formed. The temperature difference may result in the surface temperature gradient, which may cause the spreading-out of the dry-patch to lead the CHF condition.

Koizumi et al. (2010) examined the CHF in horizontal flat mini-channels. The test flow channel used is presented in Fig. 20. The top cover of the test section was made of a transparent poly-carbonate plate. The width and the length of the test flow channel were 10 mm and 240 mm, respectively. The height of the test flow channel was varied in the range of 0.184 ~ 1.014 mm. The heating test surface made of copper was located at 95 mm from the inlet of the test flow channel. The heating length was 50 mm. The heating test surface was fixed at the bottom of the test flow channel so as to be flush with the bottom wall of the test flow channel. The backside of the heating surface was heated with electric heaters. Distilled water was used in experiments.

A flow state was recorded with a high speed camera. The flow state became a slug flow with long bubbles that occupied entirely the flow channel or an annular flow even in low quality. Tiny bubbles were observed in the liquid film as the heat flux was increased. Figure 21 is the example of a flow state just before the CHF condition. The heat transfer surface is partly covered with water film. Large dried areas are observed on the heat transfer surface. The dried areas spread out and finally the CHF condition comes out. This condition is considered to be similar to the CHF occurrence condition in the forced film flow boiling that was discussed in Section 3.

The CHF obtained in their experiments are compared with the predictions by Eqs. (14) and (15) in Fig. 22. The trend of the CHF on the parameter is well expressed, however, the CHFs in the flat mini-channels are lower than those of the correlation for the downward film flow. When the flow channel size is decreased down to the mini size, the wall effect due to the viscosity that suppresses the growth of the film flow disturbance may become enhanced. Thus, as a result of the less disturbed film condition, the CHF becomes smaller than that for the downward film flow of the usual size flow path.

[DOI: 10.1299/mer.2014tep0006] © 2014 The Japan Society of Mechanical Engineers
The best fit curve of the CHF for the experimental results is

$$\frac{q_{CHF}/H_{fg}}{\rho_l u_{mcr}} = 0.0053 \times \left( \frac{\rho_g}{\rho_l} \right)^{0.08} \times \text{We}^{-0.33}. \tag{16}$$

It is again confirmed that the form of Eqs. (12), (14) ~ (16) is appropriate to predict the CHF of the film flow boiling. The only open item to be resolved is the constant in the right-hand side of the equations which expresses the degree of the film flow disturbance which has direct effect on whether the film flow can rewet the dried area or not triggering the CHF condition.

Fig. 18 CHF Experiments for Forced Flow Boiling in Vertical-Narrow-Annular Passages (Koizumi et al., 2001)

Fig. 19 Correlation of CHF of Forced Flow Boiling in Vertical-Narrow-Annular Passages (Koizumi et al., 2001)
Fig. 20 Test Section for Flat Mini-Channel CHF Experiments (Koizumi et al., 2010)

Fig. 21 Flow State just before CHF Condition (Flow from left to right) (Koizumi et al., 2010)

Fig. 22 Correlation of Flat Mini-Channel CHF (Koizumi et al., 2010)
5. Characteristics of falling film flow

As already pointed out in the former sections, the wave characteristics, such as the wave height, the wave velocity, the wave frequency, and the wavelength, are essential considering the CHF condition of the film flow boiling, including the annular flow of the forced convection flow boiling.

The characteristics of waves on a thin film that flowed down along a vertical pipe were studied by Telles and Dukler (1970), and the statistical aspects of waves on the film were discussed. Takahama and Kato (1980) examined the flow characteristics of the water film falling down along the outer wall of a circular tube without concurrent gas flow. The wave motion on the film was measured using needles and an electric capacitance method. They reported data on the wave velocity and the wave peak height. Karapantsios et al. (1989) studied the characteristics of water films flowing down inside a vertical pipe. They focused on very high Reynolds number film flow and reported mean film thickness data and wave amplitudes. Nosoko et al. (1996) conducted falling film experiments producing well regulated waves on a water film that flowed down along a flat plate. They proposed correlations for the wave velocity and the peak wave height. Since the wave separation was artificially controlled, the wavelength information is required in their correlations. Kurabayasi et al. (1999) and Takamasa and Kobayashi (2000) measured the characteristics of waves of a water film that flowed down along the inner wall of a vertical pipe by a sophisticated method using a laser focus displacement meter. Data of the wave velocities and the maximum, the minimum, and the average film thickness were reported. Koizumi et al. (1999, 2000 and 2001) investigated falling films of water and R-113 along the outer wall of vertical pipes. Wave motion was measured using a visual technique and an electric capacitance method. The wave velocity, the minimum, the maximum, and the mean film thickness, and the wavelength were reported.

Koizumi et al. (2009) examined the behavior of a film that flowed down along the inner surface of a vertical pipe in the counter-current flow condition on the bases of the above background. Water and viscous fluids of silicone oils; 500, 1,000, and 3,000 cSt were used as the liquid phase. The gas phase is air. Considering that the characteristics of waves on the film should be determined by only the superficial conditions, such as the mass flow rate of liquid and the flow path dimension, new general correlations have been proposed for the wavelength, the wave velocity, and the maximum film thickness.

The experimental apparatus used in Koizumi et al. (2009) is shown schematically in Fig. 23. Experiments were conducted at room temperature and atmospheric pressure. The test section was a vertical circular Plexiglas pipe with the inner diameter of 30 mm and the length of 5.4 m. The wall thickness was 5 mm. Test liquid flowed into the test section through a 200 μm mesh sintered-metal. It flowed down gravitationally along the inner wall of the test section as a film. A vacuum was connected to the top of the test flow channel. Air was sucked from the bottom of the test flow channel. The bottom entrance of the test flow channel had a bell mouth configuration to allow air to smoothly flow into the test flow channel.

A film flow on the test pipe wall was visualized as shown in Fig. 24. Fluorescent dye (Rhodamine B) was dissolved into test liquid. An Ar laser ray sheet of 5 W was emitted toward the flow so as to be parallel to the center line of the test pipe and to pass through the center line. The dye in the liquid film on the test pipe wall then fluoresced along the laser ray. The luminous plane was recorded by a CCD video camera and a high-speed video camera from the side. The variation of the film thickness with time, and also the average, the minimum, and the maximum film thicknesses were derived from the recorded images.

A large peak was selected in the recorded images, and then the velocity of the wave was determined from the traveling distance of the peak during elapsed time. The interval between neighbouring two large peaks was measured as the wavelength.

5.1. Wave profile

The film thicknesses measured are presented in Figs. 25 and 26. The air velocity is zero in these cases. Figure 25 shows the data for water, and Fig. 26 shows the data for 500 cSt silicone. The film thicknesses are plotted against time in Figs. 25 (a) and 26 (a). In Figs. 25 (b) and 26 (b), the horizontal axes are converted into the axial length using the wave velocity. The dotted lines in the figures denote the mean film thickness.

Large waves are found on the thin substrate in Fig. 25. Periodical variations are also observed in Fig. 26. However, the number of large waves is less than in the water film case. The thickness of the substrate is approximately equal to the mean film thickness. There are a few small waves.
between the large waves, and the wave surface appears smooth.

Fig. 23 Experimental Apparatus for Wave Characteristics Measurement (Koizumi et al., 2009)

Fig. 24 Measurement of Film Thickness (Koizumi et al., 2009)
Fig. 25 Variation of Film Thickness (Water Film) (Koizumi et al., 2009)
Fig. 26 Variation of Film Thickness (Silicone 500 cSt Film) (Koizumi et al., 2009)
5.2. Film thickness

The mean, the maximum, and the minimum film thicknesses of water and silicone films are plotted against the film Reynolds number

\[ \text{Re}_f = \frac{4\Gamma}{\mu} \]  \hspace{1cm} (17)

in Figs. 27 and 28. Here, \( \Gamma \) is the film flow rate per unit width, and \( \mu \) is the viscosity of the liquid. The air velocity is zero in Fig. 27. The condition of Fig. 28 is near the onset of flooding.

In the counter-current flow condition, as the air flow rate was increased, part of liquid that flowed into the test pipe through the sintered metal section was suddenly initiated to flow upward above the liquid inlet and out from the top of the test pipe. This is the initiation of flooding. The air flow rate at the flooding initiation took a different value, depending on the test condition of the liquid flow rate. The film thicknesses presented in Fig. 28 were measured just before the initiation of flooding.

The dashed lines in Figs. 27 and 28 are the values of the Nusselt film thickness correlation for the laminar falling film (Ueda (1981c) and Kandlikar et al. (1999)):

\[ y_{in}^* = (3/4)^{1/3} \text{Re}_f^{1/3}, \]  \hspace{1cm} (18)

where \( y_{in} \) is the Nusselt film thickness, \( g \) is the gravitational acceleration, and \( \nu \) is the kinematic viscosity. Here, \( y_{i}^* \) is the dimensionless film thickness = \( y_i (g/\nu^2)^{1/3} \).

The solid lines in Figs. 27 and 28 denote the film thicknesses calculated by the following equations:

\[
\begin{align*}
\text{Re}_f & = 2(y_i^+)^2 & y_i^+ \leq 5, \\
\text{Re}_f & = 50 - 32.2y_i^+ + 20y_i^+ \ln y_i^+ & y_i^+ \leq 30 \quad \text{and} \\
\text{Re}_f & = -256 + 12y_i^+ + 10y_i \ln y_i^+ & y_i^+ > 30.
\end{align*}
\]  \hspace{1cm} (19)

Here, \( y_i \) is the film thickness and \( y_i^+ = (y_i/\nu)^{1/2}(\tau_w/\rho)^{1/3} \). The symbol \( \tau_w \) is the wall shear stress, and \( \rho \) is the liquid density. Equation (19) is derived by applying the Karman universal velocity profile for a single-phase flow to the falling film flow (Ueda (1981c), Kandlikar et al. (1999) and Whalley (1987)).

The mean film thicknesses are well expressed by Eqs. (18) and (19) in Figs. 27 and 28, although Eq. (19) gives slightly better results. Note that the agreement between the measured and the predicted film thicknesses is not affected by the existence of the air flow until the occurrence of flooding. This suggests that the upward air flow has little effect on the film thickness before the initiation of flooding.

When there is no air flow; Fig. 27, the maximum film thicknesses of the water film and the 500 cSt and 1000 cSt silicone films are much larger; 1.5 ~ 3 times larger, than the mean film thicknesses. This suggests that there are large waves on the film. However, in the case of 3000 cSt silicone film, there are no waves on the film.

At the condition just before the flooding initiation shown in Fig. 28, the amplitudes of the waves of the water, the 500 cSt silicone films are much larger; 1.5 ~ 3 times larger, than the mean film thicknesses. This suggests that there are large waves on the film. However, in the case of 3000 cSt silicone film, there are no waves on the film.

5.3. Wave velocity

If a laminar falling film with a smooth-flat surface on a vertical wall is assumed, the velocity profile in the film is derived from Newton’s law. This is the Nusselt falling film. The film thickness \( y_{in} \) of the Nusselt falling film is given in dimensionless form by Eq. (18). The film velocity \( u_{in} \) at the surface \( y_{in} \) and the mean film velocity \( u_{mn} \) are expressed respectively as follows:

[DOI: 10.1299/mer.2014tep0006] © 2014 The Japan Society of Mechanical Engineers
\[
\begin{align*}
  u_{iN} &= \frac{1}{2} \frac{pg}{\mu} y_{iN}^2, \\
  u_{iN} &= \frac{2}{3} u_{iN}.
\end{align*}
\]

When small perturbation waves on the film surface are considered, the velocity of the small perturbation waves \( u_{spw} \) (Carey (1992)) is
\[
  u_{spw} = 2u_{iN} = 3u_{mN}.
\]

Here, \( \mu \) is the viscosity of the film.

Considering the dimensionless form of the wave velocity \( u_{w} \), \( N_{uw} = u_{w}/(g\sqrt{\nu})^{1/3} \). Thus, the expression for the surface velocity of the Nusselt film is
\[
(N_{uw})_{N} = \left( \frac{1}{2} \right)^{2/3} \left( \frac{3}{4} \right)^{2/3} Re_t^{2/3}
\]
and the expression for the velocity of the small perturbation waves on the Nusselt film is
\[
(N_{uw})_{spw} = 2(N_{uw})_{N}.
\]

The wave velocities obtained in experiments are shown in dimensionless form in Fig. 29. The values calculated by Eqs. (23) and (24) are included in the figure for comparison. The data of Koizumi et al. (1999, 2000) for the film on the outer wall of the vertical pipes for water and R-113, the data of Takahama and Kato (1980) for the water film on the outer wall of a vertical pipe, and the data of Kurabayasi et al. (1999) and Takamasa and Kobayashi (2000) for the water film on the inner wall of a vertical pipe are also plotted in the figure.

When the film Reynolds number is low; \( Re_f \leq 600 \), the wave velocities of either water or R-113 are well expressed by Eq. (24) for the small perturbation waves on the smooth film (the Nusselt film). It is suggested that the waves are on the laminar falling film of the smooth surface of the Nusselt film and behave like small perturbation waves of sine-wave form.

When the film Reynolds number is large, i.e., \( Re_f > 600 \), the wave velocity becomes slower than the Nusselt film surface velocity. Large waves existed on the substrate of the film. The substrate is much thinner than the Nusselt film. The film velocity at the substrate thickness is much slower than the Nusselt film surface velocity. Thus, it is natural that the wave velocity on the substrate becomes slower than the Nusselt film surface velocity.

5. 4. Wavelength

The wavelengths for water and silicone measured in the experiments are plotted with respect to the film Reynolds number in Fig. 30. It is difficult to say that the wavelength is a function only for the film Reynolds number.

Following dimensionless parameters were found through the dimensional analysis:

\[
N_{\lambda}' = \frac{\lambda}{h},
\]

\[
Fr = \frac{u_{w}}{\sqrt{gh}}
\]

and the film Reynolds number (given in Eq. (17)), where \( h \) is the mean film thickness, \( u_{w} \) is the wave velocity, and \( \lambda \) is the wavelength. For the present experimental results,
\[ N_\lambda = 14.9 \text{Fr}^{1.29} \text{Re}_f^{-0.133} \]  \hspace{1cm} (27)

is obtained as the best fit form. The values predicted by Eq. (27) are in good agreement with the experimental results as shown in Fig. 31.

5.5. Development of correlations of wave properties

When the dimensional analysis about the wave properties of the wave velocity \( u_w \) and the maximum film thickness \( h_p \) is performed using the Buckingham \( \pi \) theorem, five dimensionless parameters are derived:

- Dimensionless wave velocity \( N_{uw} = \frac{u_w}{(\nu g)^{1/3}} \)

- Dimensionless maximum film thickness \( N_{hp} = h_p \left( \frac{g}{\nu^2} \right)^{1/3} \)

- Dimensionless wavelength \( N_\lambda = \lambda \left( \frac{g}{\nu^2} \right)^{1/3} \)

- Morton number \( K_F = \frac{\rho^3 \nu^4 g}{\sigma^3} \)

and the film Reynolds number. Here, \( \sigma \) is the surface tension.

Nosoko et al. (1996) proposed the correlations for the wave velocity and the maximum film thickness based on the dimensionless parameters. However, the Nosoko correlations require knowledge of the wavelength. The correlations are not closed.

It is desirable that the wave velocity and the maximum film thickness be evaluated only from the film flow rate and the physical dimensions. The correlations that require only the film flow rate that is give at the boundary, the physical dimensions, and the physical parameters are developed.

The wavelength correlation of Eq. 27 was incorporated with the Nosoko correlations. Then, the constants and exponents were adjusted to provide better results. The final forms were obtained as follows:

\[ N_{uw} = 0.88K_F 0.008 \text{Fr}^{0.977} \text{Re}_f^{0.214} \text{ and } \] \hspace{1cm} (32)

\[ N_{hp} = 1.09K_F 0.021 \text{Fr}^{0.316} \text{Re}_f^{0.424} . \] \hspace{1cm} (33)

Figures 32 and 33 provide a comparison of Eqs. (32) and (33) with experimental values. In these figures, the data of Takahama and Kato (1980) for water films, the data of Nosoko et al. (1996) for water films, the data of Kurabayasi et al. (1999) and Takamasa and Kobayashi (2000) for a water film, and the data of Koizumi et al. (1999, 2001) for water and R-113 films are also shown. The correlations could predict the experimental values to an accuracy of within 20%.

In the preceding section, it was mentioned that the films tend to show different behaviors in Fig. 29 when the film Reynolds number \( \text{Re}_f \) exceeded 600. Thus, it is better to develop correlations for each region separately. Therefore, the following correlations were derived for each region:

\[ N_{uw} = 0.86K_F 0.013 \text{Fr}^{0.582} \text{Re}_f^{0.429} \quad (\text{Re}_f \leq 600), \] \hspace{1cm} (34)

\[ N_{hp} = 1.11K_F 0.019 \text{Fr}^{0.693} \text{Re}_f^{0.229} \quad (\text{Re}_f \leq 600), \] \hspace{1cm} (35)

\[ N_{uw} = 3.97K_F 0.008 \text{Fr}^{0.348} \text{Re}_f^{0.255} \quad (\text{Re}_f > 600) \] \hspace{1cm} and \hspace{1cm} (36)

\[ K_F = \frac{\rho^3 \nu^4 g}{\sigma^3} \]
\[ N_{hp} = 0.18 K_F^{0.031} F_{r}^{1.15} R_e^{0.381} \quad (R_e > 600). \]  

(37)

The values predicted by these correlations are compared with measured values in Figs. 34 through 37. The results are slightly better than Eqs. (32) and (33). Note that the data of Takamasa et al. (1999, 2000) show a different trend from the other data. The reason for this is not clear. They adopted the laser focus displacement method to obtain the wave characteristics. In this method, most of the waves, including small ripples on the surface, were detected. In other studies, the wave characteristics were mainly obtained visually. Naturally, the small ripples were excluded in the visual data acquisition process. This may be the reason for the discrepancy in the figures. Finally, note that large waves are important when phenomena such as the critical heat flux are considered.

Fig. 27 Film Thickness (U_g = 0) (Koizumi et al., 2009)
Fig. 28 Film Thickness (Ug: Near Onset of Flooding) (Koizumi et al., 2009)
Fig. 29 Wave Velocity (Koizumi et al., 2009)

Fig. 30 Wavelength (Koizumi et al., 2009)
Fig. 31 Correlation of Wavelength (Koizumi et al., 2009)

\[
\frac{\lambda}{h} = 14.9 Fr^{1.29} Re^{-0.133}
\]
Fig. 32 Wave Velocity (Koizumi et al., 2009)

\[ N_{uw} = 0.88K_F^{0.008}F_r^{0.977}Re_f^{0.214} \]

± 20\%

- Water
- Silicone 500 cSt
- Silicone 1,000 cSt
- Koizumi (R-113)
- Koizumi (Water)
- Takahama (Water)
- Takamasa (Water)
- Nosoko (Water)
Figure 33: Maximum Film Thickness (Koizumi et al., 2009)

\[
N_{hp} = 1.09 K_F^{0.021} F_r^{0.316} R_e_f^{0.424}
\]

\[\pm 20\%\]

Figure 34: Wave Velocity (Re_f \leq 600) (Koizumi et al., 2009)

\[
N_{uw}/K_F^{0.013} F_r^{0.582} = 0.86 R_e_f^{0.429}
\]

\[\pm 15\%\]
Fig. 35 Maximum Film Thickness (Re_f ≤ 600) (Koizumi et al., 2009)

Fig. 36 Wave Velocity (Re_f > 600) (Koizumi et al., 2009)
6. Concluding remarks

It has been considered that the deterioration of heat transfer on the heat transfer surface results in the occurrence of the critical heat flux (CHF) condition in forced flow boiling. The appearance of stable dry-patches on the heat transfer surface, whether these are partially or not, results in the deterioration of heat transfer to cause the CHF condition. In forced flow boiling, the CHF condition occurs in annular flow in many cases. Thus, to examine the formation of the dry-patch in the film flow boiling provides much valuable information for considering the CHF condition. Taking it into account, the minimum wetting rate was discussed in the first part. Then, the CHF of the falling film boiling and upward flow boiling was examined in the second part. The CHF correlation developed was applied to the flat mini-channels in the third part. Finally, the characteristics of waves on a falling film which is required to deal with the minimum wetting rate or the CHF was introduced in the fourth part. Materials used in those discussions were mainly the accomplishment of the present author.

1. Minimum wetting rate

The minimum wetting rate (MWR) was defined such as the minimum film flow rate at which the dry-patch was rewetted by the film. Since there were large waves on the film, the MWR was greatly affected by the waves. The contact angle of the film at the top edge of the stable dry-patch varied periodically synchronizing with the arrival of the waves. When the contact angle exceeded the maximum advancing contact angle, the top edge of the dry-patch began to
move downward, i.e. the rewetting of the dry-patch was initiated. The MWR was properly given by considering that the dry-patch is rewetted when the maximum of the dynamic pressure of the film fluctuating according to the waves exceeds the upward component of the surface tension corresponding to the maximum advancing contact angle at the top edge of the dry-patch.

2. Critical heat flux of film flow

Many tiny bubbles were observed in the film in the falling film boiling and the upward flow boiling. The bubble generation in the film might create a dry-patch locally in the film. If the film flow coming to the dry-patch could not rewet it, the CHF condition occurred. In the falling film boiling, the long film flow might have a larger disturbance of the film flow than the short film flow. Thus, the CHF of the long falling film boiling was larger than the CHF of the short falling film boiling. The disturbance of the film flow of upward flow boiling was larger than that of the falling film boiling. Thus, the CHF of the upward flow boiling was larger than the CHF of the falling film boiling. The CHF of those were predicted with a unique correlation except for the constant that expressed the difference of the degree of the disturbance of the film flow.

3. Critical heat flux of mini channel

The CHF of the flat mini-channels were predicted with the CHF correlation for the upward flow boiling and the falling film boiling except the constant. The constant, i.e. the CHF, was lower than of course the CHF of the upward flow boiling and also than the CHF of the falling film boiling. Since a wall effect due to the viscosity that suppressed the growth of the disturbance of the film flow was enhanced in the flat mini-channels, the disturbance of the film flow on the heat transfer surface was reduced and the CHF might become smaller.

4. Characteristics of falling film flow

Correlations for the wavelength, the maximum film thickness and the wave velocity were introduced. The proposed correlations required only a film flow rate, physical parameters and geometrical dimensions. These values of the wave characteristics were required in the correlations of the MWR and the CHF. What is left toward the next step is to incorporate these characteristics of the waves with the MWR and CHF correlations.

References

Bankoff, S. G., Minimum thickness of a draining liquid film, International Journal of Heat and Mass Transfer, Vol.14 (1971), pp.2143-2146.
Carey, V. P., Liquid-vapor phase-change phenomena, Hemisphere Publishing Company (1992), pp.106-112.
Hartley, D. E. and Murgatroyed, W., Criteria for the break-up of thin liquid layers flowing over solid surfaces, International Journal of Heat and Mass Transfer, Vol.7 (1964), pp.1003-1015.
Hewitt, G. F. and Lacey, P. M. C., The breakdown of the liquid film in annular two-phase flow, International Journal of Heat and Mass Transfer, Vol.8 (1965), pp.781-791.
Hewitt, G. F. and Hall-Taylor, N. S., Annular two-phase flow, Pergamon Press, Oxford (1970), pp. 127-135.
Kandlikar, S. G., Shoji, G., and Dhir, V. K., Handbook of phase change: boiling and condensation, Taylor and Francis, Philadelphia (1999), pp.342-345.
Karapantzos, T. D., Paras, S. V., and Karabelas, A. J., Statistical characteristics of free falling films at high reynolds number, International Journal of Multiphase Flow, Vol.15, No.1 (1989), pp.1-21.
Katto, Y. and Ishii, Burnout in a high heat flux boiling system with a forced supply of liquid through a plane jet, Transactions of the Japan Society of Mechanical Engineers, Vol.44, No.384 (1978), pp.2817-2823. (in Japanese)
Katoh, K., Tsao, Y., Yamamoto, M., Fujita, H. and Azuma, T., A study on measurement of solid-liquid contact angle and surface tension, Transactions of the Japan Society of Mechanical Engineers Series B, Vol.61, No.584 (1995a), pp.1456-1461. (in Japanese)
Katoh, K., Azuma, T. and Tsao, Y., Measurement of solid-liquid contact angle and liquid surface tension (Method using inclined plate), Transactions of the Japan Society of Mechanical Engineers Series B, Vol.61, No.591 (1995b), pp.4171-4177. (in Japanese)
Koizumi, Y., Yoshinari, T., Ueda, T., Matsuo, T. and Miyashita, T., Study on dry-out heat flux of two-phase natural
circulation, Transactions of the Japan Society of Mechanical Engineers Series B, Vol.60, No.570 (1994), pp.545-551. (in Japanese)
Koizumi, Y., Matsuo, T., Miyota, Y. and Ueda, T., Dry-out heat fluxes of falling film and low-mass flux upward flow in heated tubes, Transactions of the Japan Society of Mechanical Engineers Series B, Vol.64, No.624 (1998), pp.2578-2585. (in Japanese)
Koizumi, Y., Kodama, Y., Ohtake, H., Ueda, T. and Miyashita, T., A study on the minimum wetting rate of isothermal films flowing down on outer surface of vertical pipes, Transactions of the Japan Society of Mechanical Engineers Series B, Vol.65, No.638 (1999), pp.3414-3421. (in Japanese)
Koizumi, Y., Ohtake, H., and Ikeda, S., Characteristics of a falling liquid film on the outer surface of a vertical pipe (Minimum wetting rate and waves on the film), Proceedings of 2000 ASME IMECE, HTD Vol.2 (2000), pp.197-203.
Koizumi, Y., Ohtake, H. and Fujita, Y., Heat transfer and critical heat flux of forced flow boiling in vertical-narrow-annular passages, 2001 ASME International Mechanical Engineering Congress and Exposition, (2001), CD-ROM, IMECE2001/HTD-24219.
Koizumi, Y., Ohtake, H., and Ikeda, S., Characteristics of an R-113 falling liquid film on the outer surface of a vertical pipe, 4th International Conference on Multiphase Flow (2001), CD-ROM EF1.
Koizumi, Y., Enari, R. and Ohtake, H., Correlations of wave characteristics for a liquid film falling down along a vertical wall, ASME Journal of Heat Transfer, Vol.131, No.8 (2009), pp.82901-1 - 82901-9.
Koizumi, Y., Ohtake, H. and Sato, K, Pressure drop and heat transfer of single-phase flow and two-phase boiling flow in thin-rectangular channels, 7th International Conference on Multiphase Flow (2010), CD-ROM 17.2.2.
Kurabayasi, M., Kobayasi, K., and Takamasa, T., Velocity measurement of interfacial waves on a film flowing down a vertical tube inner wall using an image-processing method and laser focus displacement meters, Proceedings of the 18th Multiphase Flow Symposium '99, (1999), pp.111-112.
Norman, W. S. and McIntyre, V., Heat transfer to a liquid film on a vertical surface, Transactions of the Institution of Chemical Engineers, Vol.38 (1960), pp.301-307.
Nosoko, T., Yoshimura, P. N., Nagata, T., and Oyakawa, K., Characteristics of two-dimensional waves on a falling film, Transactions of the Institution of Chemical Engineers, Vol. 51 (1996), pp.725-732.
Rohsenow, W. M., A Method of correlating heat transfer data for surface boiling of liquids, Transactions of ASME, Journal of Heat Transfer (1952), pp.150-154.
Takahama, H. and Kato, S., Longitudinal flow characteristics of vertical falling liquid films without concurrent gas flow, International Journal of Multiphase Flow, Vol.6 (1980), pp.203-215.
Takamasa, T. and Kobayashi, K., Measuring interfacial waves on film flowing down tube inner wall using laser focus displacement meter, International Journal of Multiphase Flow, Vol.26 (2000), pp.1493-1507.
Telles, A. S. and Dukler, A. E., Statistical characteristics of thin, vertical, wavy, liquid films, Fundamentals of Chemical Engineering, Vol.19, No.3 (1970), pp.412-421.
Ueda, T., Inoue, M. and Nagatome, S, Critical heat flux and droplet entrainment rate of falling liquid films with boiling, Transactions of the Japan Society of Mechanical Engineers Series B, Vol.47, No.419 (1981a), pp.1341-1348. (in Japanese)
Ueda, T. and Isayama, Y., Critical heat flux and exit film flow rate in a flow boiling system, Transactions of the Japan Society of Mechanical Engineers Series B, Vol.47, No.423 (1981b), pp.2191-2198. (in Japanese)
Ueda, T., Two-phase flow and heat transfer, Yokendo Co., Ltd, Tokyo (1981c), pp.125-127, 128-132, 200-219. (in Japanese)
Whalley, P. B., Boiling, condensation, and gas-liquid flow, Oxford University Press, New York (1987), pp.29-31.