Film Boiling Heat Transfer and Minimum-Heat-Flux (MHF)-Point Condition in Subcooled Pool Boiling*

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The minimum-heat-flux (MHF)-point condition and film-boiling heat transfer in subcooled pool boiling of water were experimentally investigated by using a horizontal cylinder and a sphere. First, collapse behavior of vapor films was observed, and it was found that collapse modes can be classified into coherent and propagative collapses. Second, the relation between the MHF-point temperature and the propagation rate of film collapse was experimentally obtained, and the MHF-point temperature at which coherent collapse occurred was defined as its true value. The experimental data obtained show that the true MHF-point temperature is not strongly dependent on liquid subcooling and it does not exceed the liquid's maximum, metastable superheat temperature even at large subcoolings. Finally, using the experimental data of subcooled film-boiling heat transfer for various liquids, a prediction technique based on Hamill's correlation was developed.

Key Words: Thermal Engineering, Heat Transfer, Phase Change, Pool Boiling, Subcooled Film Boiling, Minimum Heat Flux

1. Introduction

In recent years, interest in subcooled film boiling and its destabilization has revived because of the advent of novel cooling problems such as rapid quenching to produce amorphous metals and the thermo-mechanical control process (TMCP) to control the metallurgical structure of steel.

As is well known, the assessment of film boiling destabilization is also of importance when considering the reliability of the ECCS in LWRs, the thermal stability analysis of superconductors, and the modeling of vapor explosions. Therefore, attempts have been made by several investigators to understand the mechanism of film boiling destabilization and the condition at the minimum-heat-flux (MHF)-point ($\Delta T_M, q_M$). These attempts have either relied on analytical derivation or experimental correlation, and they have been summarized in a previous report by

one of the present authors⁽¹⁾. As pointed out in the report⁽¹⁾, each of the existing models and correlations of the MHF-point condition implicitly premises either a temperature-controlled or heat-flux-controlled hypothesis. In that report, based on a discussion of several aspects of the MHF-point condition in saturated pool boiling, it was concluded that the temperature-controlled hypothesis, in which the MHF-point temperature T_M is regarded to be the dominant factor, is superior to the heat-flux-controlled hypothesis. In the present report, this temperature-controlled hypothesis is examined with respect to subcooled pool boiling.

When the mechanism of the destabilization of subcooled film boiling is interpreted from the viewpoint of the temperature-controlled hypothesis, one experimental fact comes into question. Namely, most of the experimental data on the MHF-point temperature of atmospheric water at large liquid subcoolings^{(2)~(7)} refer to values which are much higher than the liquid's maximum, metastable superheat temperature T_{is} . For example, Dhir and Purohit⁽⁵⁾ reported the following correlation of T_M for atmospheric water:

$$T_M = 201 + 8\Delta T_{sub} \text{ (}^\circ\text{C)} \quad (1)$$

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and Lienhard⁽⁸⁾ derived the following correlation of T_{ls} based on thermodynamic considerations:

$$T_{ls} = (0.905 - \theta_{sat} + 0.095 \theta_{sat}^8) T_{cr} + T_{sat} \quad (2)$$

In the above equations, ΔT_{sub} is the degree of liquid subcooling, T_{sat} is the saturation temperature, T_{cr} is the thermodynamic critical temperature, and $\theta_{sat} = T_{sat}/T_{cr}$. Equations (1) and (2) indicate that the value of T_M for atmospheric water exceeds the value of T_{ls} at subcoolings of larger than 14 K. With the temperature-controlled hypothesis, however, it is usual to consider that the MHF-point temperature can not exceed the liquid's maximum, metastable superheat temperature T_{ls} or T_{ls0} , where T_{ls0} is given by:

$$T_{ls0} = (1 + \beta^{1/2})(T_{ls} - T_l) + T_l \quad (3)$$

In Eq. (3), $\beta = (\rho ck)_l / (\rho ck)_w$, where ρ , c , and k denote the density, the specific heat, and the thermal conductivity respectively, and the subscripts l and w denote the liquid and the surface material, respectively. The first purpose of the present paper is to discuss this discrepancy, focusing attention on the effect of the collapse mode of the vapor film on the MHF-point condition.

A number of analyses of film-boiling heat transfer have been reported. For example, laminar, smooth-interface film boiling has been investigated analytically by using the so-called two-phase boundary layer approximation. Reports on this type of analysis applied to pool boiling include those on saturated film boiling^{(9)~(12)}, subcooled film boiling^{(5),(13)~(18)}, and the effect of radiation heat transfer^{(19),(20)}. Recently, Sakurai et al.⁽²¹⁾ conducted experiments of the subcooled film boiling of water on horizontal cylinders, and showed that their experimental data were in good agreement with the predictions of the theoretical model derived by Nishikawa and Ito⁽¹⁶⁾. In general, however, the amount of experimental data on subcooled film boiling is not enough to provide a good understanding of the subcooled film boiling process^{(5),(17),(21)~(24)}. Therefore, the second purpose of the present paper is to determine experimentally the effects of liquid subcooling and system pressure on film-boiling heat transfer from cylindrical and spherical surfaces which are designed so that film boiling can persist well into low surface superheats, even at large liquid subcoolings.

The two-phase boundary layer equations given above are usually solved numerically. However, it is fascinating to see that analytical expressions, even if they are approximate, can estimate parametric effects. For example, Hamill and Baumeister⁽²⁵⁾ analyzed film boiling on a horizontal plate with subcooling and radiation, and showed that the total heat transfer coefficient h_{ft} could be written as:

$$h_{ft} = h_{fs} + 0.12 h_l (\Delta T_{sub} / \Delta T_{sat}) + 0.88 h_r \quad (4)$$

where h_{fs} is the convection component of the saturated film boiling heat transfer coefficient, h_l is the natural-convection heat transfer coefficient of the liquid, h_r is the radiation heat transfer coefficient, and ΔT_{sat} is the degree of surface superheat. Equation (4) provides an excellent means of surveying the parametric effects on subcooled film-boiling heat transfer, though some investigators^{(22)~(24)} have pointed out that they found it necessary to modify the value of the proportionality constant of the second term on the right-hand side of Eq. (4) in order to explain their own data. Thus, the third purpose of the present paper is to propose a general form of Eq. (4).

2. Experimental Apparatus and Data Reduction

The test liquid used was water, and two different boiling surfaces made of platinum were used: a horizontal cylinder of diameter $D=2$ mm and a sphere of $D=10$ mm.

2.1 Cylindrical surface

Figure 1 is a schematic diagram of the horizontal, cylindrical surface used in the experiment. The test surface was a platinum cylinder (at least 99.99% pure) of $D=2$ mm. To eliminate the so-called end effects, the cylinder was bent into a U-shape and was connected to electrodes in an air atmosphere. It was directly heated by direct current supplied from a stabilized DC-power supply through the electrodes. The electric current supplied was measured with a standard resistor inserted in series in the electric circuit. Two fine 0.03 mm-diameter platinum wires were spot-welded as potential taps to the platinum cylinder with about 40 mm apart at the central portion of the cylinder. The heat generated in the cylinder was calculated from electric current measurement across the standard resistor together with voltage drop

Fig. 1 Schematic diagram of cylindrical surface

measurement across the potential taps. The average temperature along the test section was determined by the dependence on temperature of the electrical resistance of platinum. It was found from a calibration test that the maximum error in the measurement of ΔT_{sat} was less than 0.5%.

Using this cylindrical surface, the two kinds of experiment described below were conducted. The first was a transient experiment in subcooled water at atmospheric pressure, to measure the MHF-point temperature and observe the collapse mode of vapor film. Having established low-superheat film boiling around the cylinder, the electric current supplied to the cylinder was rapidly decreased to a finite value. During this cooldown period, temperature-time data of the cylinder were recorded, and the collapse behavior of the vapor film was observed with a high-speed video motion-analyzer system (200 frames/s). Using the temperature-time data together with the lumped thermal-parameter approximation, the MHF-point temperature was determined by the boiling curve calculated from the following equation:

$$q_w = q_j - (\rho c)_w \left(\frac{V_w}{A_w} \right) \left(\frac{dT_w}{dt} \right) \quad (5)$$

where q_j is the heat generated in the cylinder per unit heat transfer area, V_w and A_w are the volume and heat transfer area of the test surface, respectively, and T_w is the temperature of the test surface. In this experiment, the system pressure p was kept at atmospheric pressure and the experimental range of liquid subcooling was from 0 to 30 K. The second test using the cylindrical surface was a steady-state experiment to determine the effects of liquid subcooling and system pressure on film-boiling heat transfer. Namely, steady-state tests of film boiling in subcooled water were repeated by reducing the DC-power supply step by step. In these steady-state experiments, the experimental ranges of system pressure and liquid subcooling were from 12.5 to 100 kPa and from 0 to 40 K respectively.

2.2 Spherical surface

Figure 2 is a schematic diagram of the spherical surface used in the experiment. The sphere was made of platinum and its diameter was $D=10$ mm. A platinum tube with an outer diameter of 2 mm was soldered to the sphere. A R-type sheath thermocouple of a diameter of 1 mm was inserted through it and was silver-soldered to the center of the sphere. Because of experimental limitations, only transient tests were conducted with this spherical surface in subcooled water at atmospheric pressure. The sphere was heated up to an initial temperature (about 1500 K) by a gas burner, then it was immersed into a water bath at a prescribed subcooling. During this cooldown period,

temperature-time data of the sphere was recorded with a pen recorder, and the boiling curve was calculated from Eq.(5), with $q_j=0$. In this case, the following points must be noted: in boiling experiments with spheres, there is a possibility that a precursory collapse of vapor film at the stem supporting the sphere forces the vapor film around the sphere to collapse before its spontaneous destabilization. Therefore, in the present experiment, the immersion depth of the sphere was varied from $0.75D$ to $3D$, to investigate the effect of precursory collapse. In this experiment, liquid subcooling was varied from 0 to 75 K, and it was found that the change in liquid subcooling during each experiment was less than 5% at a location 10 mm horizontally away from the sphere.

3. Collapse Mode of Vapor Film and True MHF-Point Temperature

3.1 Collapse mode of vapor film

The collapse mode of a vapor film has a close relation to the MHF-point condition. For example, Iløe et al.⁽²⁶⁾ isolated three different control mechanisms for forced convection rewetting. In the present paper, the collapse mode of vapor film around the horizontal cylinder was observed by using the video system described above. From the results of observation, it was found that the collapse mode could be classified into the following two types.

(A) Coherent collapse: A vapor film collapses almost simultaneously over the heat transfer surface (see Fig.3(a)).

(B) Propagative collapse: A precursory local collapse of a vapor film propagates along the heat transfer surface, bringing about the total collapse of the vapor film (see Fig.3(b)).

Firstly, propagative collapse observed in the pres-

Fig. 2 Schematic diagram of spherical surface

ent experiment means a collapse mode in which a precursory local collapse triggered by a weak spot with respect to the vapor film propagates at a relatively slow rate along the cylinder surface, bringing about the total collapse of the vapor film in the same way as in the propagation of the quench point during the reflooding phase in LWRs. Therefore, a strong temperature gradient along the cylinder seems to be created during the propagation of the precursory collapse, and the propagation of the film collapse is considered to be controlled by axial thermal conduction along the cylinder. On the other hand, coherent collapse means a collapse mode in which propagation of local collapse cannot be clearly observed, and in which the vapor film collapses totally over the cylinder surface within the time interval of a video frame (5 ms). In this case, even if propagation of local collapse occurred within this time interval, its calculated propagation rate must be higher than 10 m/s because the length of cylinder on the video film was 50 mm. In comparison, the rate of expansion of a liquid-solid contact during the impact of a water drop on a solid surface at room temperature is about 5 m/s for a falling height of 20 mm⁽²⁷⁾. These facts indicate that a total collapse which occurs within the time interval of a video frame can be regarded as coherent collapse, not as propagative collapse controlled by axial thermal conduction.

To investigate the relation between the MHF-point temperature and the collapse mode, the average rate of propagation of precursory collapse along the photographed length of the cylinder (50 mm) v_{wf} was

Fig. 3 Collapse modes of vapor film

measured during the observation. The experimental results are shown in Fig. 4. As shown in Fig. 4, the MHF-point temperature has a close relation to the propagation rate.

When a precursory local collapse triggers the total collapse of the vapor film, a large temperature gradient must be created along the heat transfer surface, as shown in the experiments of Bergles and Thompson⁽²⁸⁾. In this case, the MHF-point temperature is measured as the average temperature of the rewetted and film boiling parts of the cylinder. Namely, the higher the measured value of the MHF-point temperature, the larger the temperature gradient created along the boiling surface. Such a large temperature gradient slows down the spreading rate of collapse of the vapor film. When the propagation rate was larger than a few m/s, it was difficult to distinguish propagative collapse from coherent collapse, and the experimental value of T_M was almost independent of v_{wf} . In Fig. 4, the average value of T_M in this region and its uncertainty are shown for each of the subcoolings by dot-dash lines and shaded regions, respectively. The results plotted in Fig. 4 show that the experimental value of T_M decreases as the propagation rate increases, and approaches the average value stated above. In the region where the value of T_M is almost constant, it is considered that the measured MHF-point temperature corresponds to the true destabilization condition because, as stated above, the estimated rate of possible propagation is of the same order of magnitude as the rate of isothermal expansion of a liquid-solid contact. Consequently, in the present report, the MHF-point temperature with

Fig. 4 Relation between propagation rate of film collapse and MHF-point temperature (---: average value of T_{RM} ; ///: uncertainty in T_{RM} ; - · - · -: Equation (1))

coherent collapse is called the true MHF-point temperature, T_{RM} . The dot-dot-dash lines in Fig. 4 indicate the predictions obtained from Eq. (1) at each of the subcoolings. As can be seen from the figure, the existing data represented by Eq. (1) correspond to those with propagative collapse whose propagation rate is shown within the vertical broken lines.

3.2 True MHF-point temperature

In Fig. 5, typical results of boiling curve obtained at $\Delta T_{sub} = 30$ K on the spherical surface are shown for different immersion depths. In the figure, experimental data for transition and nucleate boiling regimes are also plotted, but they are only shown for reference. As can be seen from the figure, the heat flux in film boiling increases with increasing immersion depth, but this tendency disappears for immersion depths of larger than $1.8D$. As for the collapse mode of the vapor film, coherent collapse was observed only for immersion depths of less than $1.8D$, and propagative collapse resulting from a precursory collapse at the supporting stem was observed for $H = 3D$. Therefore, the value of T_{RM} at each of the liquid subcoolings for the spherical surface was determined from the boiling curve for immersion depths of less than $1.8D$, and that for the horizontal cylinder was determined by the dot-dash lines in Fig. 4.

The experimental values of T_{RM} determined in this way are plotted against liquid subcooling in Fig. 6. As can be seen from the figure, the values of T_{RM} for cylindrical and spherical surfaces are in good agreement with each other. The solid lines in Figs. 4 and 6 show the value of T_{RM} calculated from the author's

correlation of T_M during saturated pool boiling⁽¹⁾ and it is in good agreement with the present data at $\Delta T_{sub} = 0$ K. In the figure, the existing correlations of T_M for atmospheric water⁽³⁾⁻⁽⁶⁾ are also shown. Comparing the present data with Eq. (1), it was found that the dependence of T_{RM} on liquid subcooling is very weak and is more similar to that of Witte and Henningson⁽³⁾. The dot-dash line shows the value of T_{iso} given by Eqs. (2) and (3). The true MHF-point temperature does not exceed this value much. This feature of the true MHF-point temperature does not conflict with the temperature-controlled hypothesis.

4. Effect of subcooling on film-boiling heat transfer

4.1 Effect of liquid subcooling on film-boiling heat transfer

Figure 7 shows the effect of liquid subcooling on the total film boiling heat transfer coefficient (h_{ft}) with a sphere at $H = 1.8D$. The data shown in the figure indicate that the total heat-transfer coefficient increases almost linearly with liquid subcooling, and that the effect of subcooling on h_{ft} becomes weak with increasing surface superheat. These facts are at least in qualitative agreement with the prediction of Eq. (4).

4.2 Development of correlation

Even if correlating approaches such as that of Eq. (4) are valid, the estimation of the second term on the right-hand side of Eq. (4) is questionable because the proportionality constant of this term reported by Siviour and Ede⁽²²⁾ is much larger than that of Eq. (4).

Frederking and Hopfenfeld⁽¹⁵⁾ obtained analyti-

Fig. 5 Boiling curve for sphere ($\Delta T_{sub} = 30$ K)

Fig. 6 Data of true MHF-point temperature

cally the following expression for total film-boiling heat transfer coefficient for the extreme case of very high subcooling :

$$h_{ft} = C[R, Pr_{lf}](k_{lf}/D)(Gr_{lf}Pr_{lf})^{1/4} \quad (6)$$

where Gr is the Grashof number, Pr is the Prandtl number, k is the thermal conductivity, the subscript lf indicates the physical properties evaluated at the liquid's film temperature, and

$$R = (\rho\mu)_{vs}/(\rho\mu)_{ls} \quad (7\cdot a)$$

$$C[R, Pr_{lf}] = func.[R, Pr_{lf}] \quad (7\cdot b)$$

In Eq. (7·a), μ is the viscosity and the subscripts vs and ls denote saturated vapor and liquid, respectively. Comparing Eq. (6) with Eq. (4), it is considered reasonable that Eq. (4) should be rewritten as the following weighted sum :

$$h_{ft} = h_{fs} + C[R, Pr_{lf}]h_{lc}\left(\frac{\Delta T_{sub}}{\Delta T_{sat}}\right) + 0.88h_r \quad (8)$$

where

$$h_{lc} = (k_{lf}/D)(Gr_{lf}Pr_{lf})^{1/4} \quad (9)$$

$$h_r = \frac{1}{(1/\varepsilon_w) + (1/\varepsilon_l) - 1} \left(\frac{T_w^4 - T_{sat}^4}{\Delta T_{sat}} \right) \quad (10)$$

In the above equations, σ_s is the Stefan-Boltzmann constant and ε_w and ε_l are the emissivities of the heat transfer surface and the liquid, respectively. To estimate the first term on the right-hand side of Eq. (8), a correlation of saturated film boiling obtained by Sakurai et al.⁽²⁹⁾ is used for horizontal cylinders and that of Grigoriev et al.⁽³⁰⁾ for spheres.

The solid lines in Fig. 7 are predictions obtained from Eqs. (8)~(10) with $C=0.96$. Comparing the predictions with the data, a correlating approach such

Fig. 7 Subcooled film-boiling heat transfer coefficient for sphere (—: Equations (8)~(10) for $C=0.96$)

as that of Eq. (8) is considered to be worth examining. Therefore, the value of the proportionality factor C in Eq. (8) was calculated from the present data ($p=100$ and 50 kPa) and the existing data on water^{(21),(22)}, Freon⁽¹⁷⁾ and sodium⁽²³⁾. The calculated values of C were correlated with the density-viscosity ratio R and the Prandtl number Pr_{lf} by least-square approximation, and the following correlation was obtained :

$$C = 0.067 R^{-0.23} Pr_{lf}^{0.21} \quad (11)$$

The values of C calculated from the experimental data, C_{ex} , are compared with predictions obtained from Eq. (11), C_{co} , in Fig. 8.

In Fig. 9, predictions obtained from Eqs. (8)~(11), $(h_{ft})_{co}$, are compared with the present data of h_{ft} on the horizontal cylinder. In Fig. 10, $(h_{ft})_{co}$ is also compared with other data, including the present data on the sphere, $(h_{ft})_{co}$. As can be seen from these figures, it is found that the present correlation is in good agreement with the experimental data. In this case, the parameter ranges used in the development of the present correlation are :

$$R = 1.5 \times 10^{-6} \text{ to } 7 \times 10^{-4}, Pr_{lf} = 0.004 \text{ to } 4.4$$

In the development of the above correlation, the proportionality constant of the radiation term has been taken to be 0.88. This is the value used in Hamill's correlation (Eq. (4)). The values of the ratio h_r/h_{ft} calculated from the experimental data used to derive Eq. (11) are smaller than 10% for water and Freons, but they are not so small for sodium (26-55%). Further, in the derivation of Eq. (11), sodium is the only liquid whose Prandtl number is very different from unity. Thus, the value of the

Fig. 8 Proportionality factor in Eq. (8) (○: horizontal cylinder; ●: sphere)

Fig. 9 Comparison between present correlation and data for horizontal cylinder (—: Equations (8) ~ (11))

Fig. 10 Comparison between present correlation and data (●: present data for sphere)

exponent of the Prandtl number in Eq. (11) is considered to be strongly dependent on the value of the proportionality constant of the radiation term and also on the accuracy of experiments with sodium. This point must be re-examined in future experiments.

5. Conclusions

(1) The collapse mode of vapor film can be classified into coherent and propagative collapses. The MHF-point temperature has a close relation to the collapse mode.

(2) The true MHF-point temperature, which is measured during coherent collapse, does not depend strongly on liquid subcooling, and it does not exceed the liquid's maximum, metastable superheat temperature. This feature of the MHF-point temperature does not conflict with the temperature-controlled hypothesis.

(3) The subcooled film-boiling heat transfer coefficient can be correlated by a weighted sum of the convection component of the saturated film-boiling heat transfer coefficient, the natural convection heat transfer coefficient of the liquid, and the radiation heat transfer coefficient.

(4) The proportionality factor of the liquid's natural convection term in the above correlation can be correlated as a function of the density-viscosity ratio and the Prandtl number of the liquid.

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