Heat Transfer of a Liquid-Solid Contact in a Subcooled Pool Boiling System* (The Second Burnout Regime)

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The heat flux was measured at the second burnout point of pool boiling over the range of high subcooling of 30 K to 88 K, under atmospheric pressure. The relation between the heat flux and subcooling was obtained by a mathematical model based on the mass-transfer mechanism of evaporation and condensation through a coalescent vapor bubble, and by a kinetic theory of molecules. The relationship equation gave fairly good agreement with the experimental results and showed that the second burnout heat flux did not increase unlimitedly with subcooling, but that it had a maximum value at a certain subcooling.

Key Words: Phase Change, Heat Transfer, Liquid-Solid Contact, Second Burnout, Subcooled Pool Boiling, Mass Flux, Condensation Coefficient

1. Introduction

In recent years, it has become desirable in a number of applications to have a high heat transfer coefficient for boiling. A higher heat flux can be attained in subcooled boiling than in saturated boiling. Recently confirmed was the existence of a unique phenomenon⁽¹⁾ in which the heat flux starts to increase rapidly beyond the burnout value in a high heat flux region of high subcooled pool boiling; this has attracted much interest.

In the earlier report⁽²⁾, the liquid-solid contact states on the heated surface in the transition-type boiling regime and in the minute bubble emission boiling regime for subcooled pool boiling were examined in detail by a direct technique using a void probe and by measurement of the temperature fluctuation in the heated surface. From the results obtained,

it became clear that in the minute bubble emission boiling regime, 86 percent of the heated surface area was always drying, regardless of heat flux. It was also found that the measured heat flux was far beyond the burnout heat flux and was proportional to the cube of the wall superheat. However, the corresponding boiling curve moves to a higher magnitude of wall superheat than that obtained in conventional nucleate boiling.

Now, it has been clarified through the present research that the heat flux does not necessarily increase unlimitedly with increasing wall superheat, but that there exists a critical value in the heat flux. If the heat flux slightly increases beyond this value, the wall temperature increases very rapidly and the entire heated surface becomes covered with a thin film of vapor. This critical point is called the second burnout point in order to distinguish it from the ordinary burnout point occurring in nucleate boiling.

Boiling burnout is roughly classified into two types, hydro-dynamic burnout due to instability in countercurrent vertical columns of liquid and vapor, and nonhydrodynamic burnout due to enlargement of the dried area on the heat-transfer surface. The

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ordinary burnout in nucleate boiling generally belongs to the former type and the second burnout to the latter.

Torikai et al.⁽³⁾ calculated the heat flux at the second burnout point for pool boiling over the range of low subcooling of 0 K to 20 K on the basis of the idea that the ratio of dried area to the heated surface area was dependent on heat flux, regardless of subcooling.

To the best of our knowledge, there have been few experiments for the estimation of the heat flux at the second burnout point in pool boiling under high subcooling.

In this experiment, the heat flux is measured at the second burnout point over the range of high subcooling, and the relation between the heat flux and the subcooling is obtained by a mathematical model based on the mass-transfer mechanism of evaporation and condensation through a coalescent vapor bubble, and by a kinetic theory of molecules.

Nomenclature

L : latent heat	[J/kg]
$\dot{m}_c$: mass flux of condensation	[kg/m ² s]
$\bar{\dot{m}}_c$: time mean value of $\dot{m}_c$	[kg/m ² s]
$\dot{m}_e$: mass flux of evaporation	[kg/m ² s]
$\dot{m}_0$: reference mass flux $= \rho_v a_M L / \sqrt{2\pi RT_s}$	[kg/m ² s]
q_{B0} : heat flux at the second burnout point	[W/m ²]
q_n : heat flux of nucleate boiling	[W/m ²]
q_0 : reference heat flux $= \dot{m}_0 L$	[W/m ²]
R : gas constant	[J/kg K]
S_c : surface area of a bubble	[m ²]
S_d : dried area of the heated surface	[m ²]
S_w : area of the heated surface	[m ²]
T_s : absolute temperature of saturation vapor	[K]
ΔT_{sat} : wall superheat	[K]
ΔT_{sub} : subcooling	[K]
V : volume of a bubble	[m ³]
τ : time	[s]
$\Delta\tau$: short time interval	[s]
ρ_l : liquid density	[kg/m ³]
ρ_v : saturation vapor density	[kg/m ³]
α_M : accommodation coefficient for condensation	[—]

2. Experimental Apparatus and Procedure

Figure 1 gives a schematic view of the pool boiling apparatus. The pool vessel was 320 mm by 320 mm by 300 mm, and its upper side was exposed to the atmosphere. The test liquid was water which had been purified, distilled and degassed at its saturation temperature for 30 min. The liquid level was maintained

at about 160 mm above the heated surface. The temperature of the water was regulated within ± 0.5 K by use of the indicated heater and cooler. The heat transfer surface was a conical copper block with a cylindrical tip whose surface was 10 mm in diameter and horizontal. A 0.05-mm-thick platinum foil was attached to this heating surface by a diffusion-bonding method. Before starting the experiment, the platinum boiling surface was polished by 6/0 emery paper to obtain a uniform initial surface roughness. The conical copper block, 65–70 mm in diameter, was heated by radiation from a molybdenum plate-heater.

Temperatures of the heat transfer surface were measured with thermocouples welded to a central and a peripheral part of the copper cylindrical tip. At each part, four holes of 0.5 mm in diameter were drilled with a spacing of about 1 mm in the vertical direction. The hot junction of the thermocouples consisted of the copper block itself and a 0.05 mm constantan wire spotwelded to the bottom of each hole. The temperature was recorded after the thermocouple indicated steady-state conditions. The temperature of the surface was determined by extrapolation of the measured values, and the heat flux was deduced from the temperature gradients.

Vapor bubbles on the heated surface were photographed at about 5 000 frames per second by a 16 mm high-speed camera. Each frame was magnified about four times and copied into a section paper. Then, the volumes and the surface areas of individual bubbles

Fig. 1 Schematic view of the pool boiling apparatus

were calculated by partition quadrature.

The accuracies of the measurements of the wall temperature, the heat flux and the volumes and surface areas of individual bubbles were about 1%, 8% and 8%, respectively. In the end, the accuracy of the mass flux of condensation, which was calculated on the basis of the measured values of the heat flux and the volume and the surface area of bubble, was estimated to be about 25%.

3. The Second Burnout Regime on the Boiling Curve

Figure 2 shows the average heat fluxes on a central and a peripheral part of the heated surface against the wall superheat in the boiling regime from the burnout point of nucleate boiling to the second burnout point. These boiling curves were obtained for a surface contaminated with scale-deposit after the first run, which required eight hours of boiling. However, for high subcooling of 50 K and 85 K, the boiling curve from the burnout point onwards is no longer sensitive to surface contamination, and the gradients of the boiling curves are less than in the nucleate boiling shown by a chain line in Fig. 2. For subcooling of 30 K and 35 K, the heat flux from the burnout point onwards remains nearly constant even if the wall temperature rises, so this regime is called the transition-type boiling regime⁽²⁾. For a relatively fresh surface (run 1) the boiling curve gradually proceeds to a stable film boiling, but if the heated surface contamination proceeds from this transition-type boiling

regime, the heat flux increases abruptly and the state enters the minute bubble emission boiling regime⁽²⁾ shown by a two-dotted line in Fig. 2. For low subcooling below 15 K, beyond the burnout point, the rapid increase of wall temperature is observed even on the contaminated surface, and the heat flux is nearly equal to or less than that at the burnout point. Transition into the minute bubble emission regime does not occur.

Again, paying attention to the range of subcooling above 30 K, there exists a maximum value for each subcooling in the heat flux which is located on the minute bubble emission boiling curve. A slight increase of the heat flux beyond this maximum value makes the wall temperature rise until stable film boiling is established. Then, it is concluded that the point of the maximum heat flux is the second burnout point.

The second burnout point for each subcooling of 30 K, 35 K, 50 K and 85 K is shown in Fig. 2 by the symbols $\blacktriangle$, $\blacksquare$, $\bullet$ and $\blacklozenge$, respectively.

The second burnout heat flux increases with increasing subcooling, but the influence of subcooling on the heat flux is not so great as the influence on the ordinary burnout heat flux in the nucleate boiling.

The broken line in Fig. 2 indicates the saturated boiling curve which was calculated by Torikai et al.⁽³⁾. They pointed out that the maximum point of this curve corresponded to the second burnout point for saturated boiling, and that the second burnout condition was achieved at a heat flux of $1.28 \times 10^7 \text{ W/m}^2$, a

Fig. 2 Subcooled pool boiling curves

wall superheat of 56 K and a ratio of dried area to the heated surface area of 55 percent. However, judging from our experimental results, it is questionable whether the second burnout condition can be achieved under the conditions of saturated pool boiling.

4. Behavior of Vapor Mass

In the case subcooling in the range of 30 K to 50 K, the vapor bubbles on the heated surface grow, coalescing into one large vapor mass covering the entire heated surface in the transition-type boiling regime between the nucleate boiling curve (a chain line) and the minute bubble emission boiling curve (two-dotted line) in Fig. 2. On reaching the minute bubble emission boiling curve, vapor bubbles are vigorously emitted from the heated surface into the subcooled liquid and, at the same time, collapse into a number of minute vapor bubbles.

In the case of high subcooling at 85 K, the vapor bubbles cannot grow into one large vapor mass covering the entire heated surface. Instead, they coalesce into a small vapor mass at the central part of the heated surface, while many discrete bubbles of nucleate boiling are observed along the periphery. However, at the second burnout point, the vapor bubbles grow again into one convex lens-like-shaped vapor mass covering the entire heated surface over the whole subcooling range from 30 K to 88 K. When the growth of the convex lens-like-shaped vapor mass is completed, condensation starts around the peripheral part of the heated surface and the volume of the vapor mass decreases. At the same time, the vapor mass collapses into a number of minute vapor bubbles. Immediately after collapse, the heated surface is covered by a thin vapor film. This thereby proves that there is subcooled liquid in the immediate neighborhood of the heated surface separated by the thin vapor film. After the thin vapor film is observed, the subcooled liquid breaks down this vapor film and jumps onto the heated surface and causes liquid-solid contact; at this time the vapor mass is observed to grow. In this way, liquid-solid contact with a very short period is realized, and, thus, instantaneous evaporation is established.

It was proved in the previous report⁽²⁾ that the shorter the liquid-solid contact period became, the more the heat flux increased. The liquid-solid contact must be realized under the state that the subcooled liquid jumping in the heated surface extends to a dried part and wets the surface. A factor shortening the liquid-solid contact period must be condensation capacity, which depends on the subcooling and the surface area of the vapor mass exposed to the subcooled liquid. A factor disturbing the thin vapor film

and enabling liquid-solid contact seems to be the rapid liquid-vapor exchanging action resulting from the momentary collapse of the vapor mass.

5. Estimation of Mass Flux of Condensation

In order to estimate the dried area on the heated surface at the second burnout point, a mathematical model based on the mass transfer mechanism of evaporation and condensation through one vapor mass is applicable in the same way⁽⁴⁾ as in the transition-type boiling regime, because the vapor bubbles come to grow again into one vapor mass covering the entire heated surface at the second burnout point. That is, mass going into a bubble is transported by evaporation of the liquid film on the heated surface, and mass departing from a bubble is transported by condensation into a subcooled liquid from the surface. Now, taking into account that the mass difference is equal to an increased mass of the bubble, the following Eq. (1) is given:

$$\rho_v(V_1 - V_0)/\Delta\tau = (S_w - S_{d0})\dot{m}_e - S_{c0}\dot{m}_{c0} \quad (1)$$

where a subscript 0 expresses time τ , and a subscript 1 expresses time $\tau + \Delta\tau$. ρ_v is density of saturated vapor at the system pressure, and is assumed constant and independent of time. Also, $\dot{m}_e = q_n/L$, where L is latent heat of evaporation. It is assumed that q_n maintains heat flux on a monotonous extension of the nucleate boiling curve shown in Fig. 2. The measured values are used as the values of V and S_c in Eq. (1), while $\dot{m}_c$ and S_d remain unknown. However, it has been obtained in the previous report⁽²⁾ that the ratio of the time mean value of the dried area to the heated surface area is constant and about 86 percent in the minute bubble emission regime.

$$\bar{S}_d = 0.86 S_w \quad (2)$$

Then, if the time mean value of the dried area $\bar{S}_d$ is introduced into Eq. (1), Eq. (1) can be solved by the following iterative method. That is, firstly, an arbitrary value of $\dot{m}_c$ is substituted into Eq. (1). Then, the value is corrected through iteration until $\bar{S}_d$ agrees with the required value. In this way, the time mean value of $\dot{m}_c$ is determined.

Figures 3 and 4 show the volume and the surface area of the vapor mass as a function of time at the second burnout point for subcooling of 30 K. Substituting the values read at every time interval $\Delta\tau = 0.2$ ms from Figs. 3 and 4 into Eq. (1), $\bar{m}_c = 2.55$ kg/m²s for run 1 and $\bar{m}_c = 2.60$ kg/m²s for run 2. Generally, $\dot{m}_c$ is a function of time, and decreases almost exponentially. At the beginning of vapor mass growth, a high value of $\dot{m}_c$ is obtained, and during the latter half of the departure period, $\dot{m}_c$ shows a minimum value⁽⁴⁾.

It is expected from this fact that the condensation capacity is influenced by intensity of vapor distur-

Fig. 3 Volume of the vapor mass as a function of time

Fig. 4 Surface area of the vapor mass as a function of time

bance within the vapor mass and of liquid disturbance around the vapor mass. It was found that, at the beginning of growth of the vapor mass, the vapor molecules flow past so violently within the vapor mass that a high mass flux of condensation may appear. At the latter half of the departure period, however, the flow of vapor is so slow within the vapor mass that a high value does not appear. The vapor mass detached from the heated surface into the subcooled liquid has an extremely low mass flux of condensation since supply of vapor from the heated surface is cut off⁽⁵⁾.

Judging from the experimental facts mentioned above, it is estimated that the fast flow of the vapor molecules in the vapor mass disturbs the thermal boundary layer formed within the vapor mass and contributes to the heat transfer.

Considering these circumstances, it is expected at

Fig. 5 Dried area on the heated surface as a function of time

the second burnout point that the mass flux of condensation will be nearly constant during a short period from the beginning of growth of the vapor mass to the departure because violent flow of the vapor molecules continues during the period for an adequate length of time. Thus, if we adopt the time mean value $\bar{m}_c$ instead of $\dot{m}_c$ in Eq. (1), the dried area on the heated surface is obtained as a function of time. Figure 5 illustrates the change with time of the dried area at the second burnout point for subcooling of 30 K, reduced in this way. Figure 5 proves that the heated surface is almost completely dry when the vapor mass departs from the heated surface.

6. The Relation Between Second Burnout Heat Flux and Subcooling

It is inconvenient in the estimation of $\dot{m}_c$ to use Eq. (1), because the procedure requires information on the volume and the surface area of the vapor mass which must be supplied from photographs. Furthermore the reading accuracy of the volume and surface area decreases since volume and its change with time become smaller and smaller as subcooling increases. In order to adopt a convenient method, an approximate solution can be obtained by assuming the left-hand term of Eq. (1) to be negligible, i. e., zero. In order to check up on the validity of the assumption, calculating the first and second terms on the right-hand side by substituting the numerical values ($\bar{S}_c$, $\bar{S}_d$, $\bar{m}_c$) at the second burnout point in the case of $\Delta T_{\text{sub}} = 30\text{K}$ shown in Figs. 3-5 into Eq. (1), the first term is $3.812 \times 10^{-4} \text{kg/s}$ and the second term is $3.770 \times 10^{-4} \text{kg/s}$. The difference of the two is negligibly small.

Then, the substantial heat flux considering the dried area S_d on the heated surface, that is, the measured heat flux q , can be expressed using S_d and the nucleate boiling heat flux q_n , whereby

$$q = (1 - S_d/S_w)q_n \quad (3)$$

If Eq. (1) rearranged with $\rho_v(V_1 - V_0)\Delta\tau = 0$ and the relationship equation $\dot{m}_c = q_n/L$ are substituted into Eq. (3), the equation $q = L\dot{m}_c S_c/S_w$ is obtained. Here if the time mean values $\bar{\dot{m}}_c$ and $\bar{S}_c$ at the second burnout point are adopted instead of $\dot{m}_c$ and S_c , q can be replaced by the second burnout heat flux q_{Bo} as follows:

$$q_{Bo} = L\bar{\dot{m}}_c \bar{S}_c/S_w \quad (4)$$

where both q_{Bo} and S_c are thereafter the respective time mean values. The validity of this evaluation for q_{Bo} should be checked based on the degree of consistency between the calculated and the measured values of heat flux at the second burnout point.

Now, judging from our experimental results that the disappearance velocity of the detached vapor mass at the second burnout point is very fast and that the duration required for disappearance is below 1 ms, that evaporation from the heated surface removes the heat above 10^7 W/m² in heat flux and that the heat is effectively transported into subcooled liquid by condensation, it will be not necessary to consider heat transfer resistance in the subcooled liquid surrounding the vapor mass and the effect of the heat generation induced by condensation at the liquid-vapor interface.

Robin and Snyder⁽⁶⁾ presented the mass transfer mechanism for subcooled nucleate boiling which is quite similar to the heat transfer process in a heat pipe. They approximated the mass flux of evaporation or condensation from the kinetic theory of molecules.

In the present report, we approximate $\bar{\dot{m}}_c$ in Eq. (4) with the following Eq. (5)⁽⁷⁾ by introducing the kinetic theory of molecules into Clapeyron's equation

with the perfect gas approximation relating temperature and pressure as

$$\bar{\dot{m}}_c = \frac{\rho_v}{(1 - \rho_v/\rho_l)} \frac{\alpha_M L}{\sqrt{2\pi R T_s}} \frac{\Delta T_{sub}}{T_s} \quad (5)$$

where ρ_v is saturation vapor density, ρ_l is liquid density, L is latent heat of condensation and T_s is absolute temperature of saturation vapor under atmospheric pressure. R is gas constant of water vapor, α_M is accommodation coefficient for condensation and ΔT_{sub} is under-cooling temperature at the interface between the saturation vapor and subcooled liquid, which can be regarded as being the temperature difference between the saturation vapor and subcooled liquid, that is, as being subcooling.

Since $\bar{\dot{m}}_c = 2.6$ kg/m²s for $\Delta T_{sub} = 30$ K, α_M is determined by substituting these values into Eq. (5). A value of 0.025 is obtained for water vapor.

Robin and Snyder⁽⁶⁾ assumed the accommodation coefficient equal to 1.0 under the condition of a fresh liquid surface. However, it is commonly viewed that the accommodation coefficient takes a very small value below unity if there is something impure contained in the liquid surface. The value of the accommodation coefficient reported for water vapor was various, $\alpha_M = 0.04$ was evaluated by Wyllie⁽⁸⁾ and $\alpha_M = 0.03$ was given in Katto's book⁽⁷⁾.

The value of 0.025 determined from Eq. (5) is little different from these values. Substituting Eq. (5) into Eq. (4), and defining $\dot{m}_0 = \rho_v \alpha_M L / \sqrt{2\pi R T_s}$ and $q_0 = \dot{m}_0 L$, Eq. (4) can be non-dimensionalized as follows:

$$q_{Bo}/q_0 = (\bar{\dot{m}}_c/\dot{m}_0)(S_c/S_w) \quad (6)$$

where $\bar{\dot{m}}_c/\dot{m}_0 = (1 - \rho_v/\rho_l)(\Delta T_{sub}/T_s)$ is a function of only subcooling ΔT_{sub} .

The measured values of S_c/S_w are shown against $\bar{\dot{m}}_c/\dot{m}_0$ in Fig. 6. The value of S_c/S_w decreases and approaches unity as $\bar{\dot{m}}_c/\dot{m}_0$ increases. The relation between S_c/S_w and $\bar{\dot{m}}_c/\dot{m}_0$ is approximated by the following empirical equation which is applicable in the experimental region of $S_c/S_w \geq 1.0$.

$$S_c/S_w = 1.38 - 2.60(\bar{\dot{m}}_c/\dot{m}_0) + 0.064(\bar{\dot{m}}_c/\dot{m}_0)^2 \quad (7)$$

This Eq. (7) is plotted in Fig. 6. When S_c/S_w becomes equal to unity, a very thin vapor film appears on the entire heated surface and the state changes into one of film boiling. Substituting Eq. (7) into Eq. (6), the heat flux at the second burnout is obtained as a function of only subcooling. It is given by

$$q_{Bo}/q_0 = -2.60(\bar{\dot{m}}_c/\dot{m}_0)^2 + 1.38(\bar{\dot{m}}_c/\dot{m}_0) + 0.064 \quad (8)$$

Equation (8) is also plotted in Fig. 6, showing a maximum value at $\bar{\dot{m}}_c/\dot{m}_0 = 0.2654$, that is, at $\Delta T_{sub} = 98.9$ K. This means that the second burnout heat flux does not necessarily increase unlimitedly with subcooling, but that a critical value exists. According to our observation at the second burnout point for high

Fig. 6 Burnout heat flux and surface area of the vapor mass against mass flux of condensation

subcooling, the whole of the heated surface is covered with a very thin vapor film at the moment film boiling begins.

Considering the physical meaning of S_c on the basis of the observation described above, it is realistic to consider that the critical value of the second burnout heat flux appears when $S_c/S_w=1.0$, that is, at $\bar{m}_c/\bar{m}_0=0.2462$ (from Eq. (7)) rather than at $\bar{m}_c/\bar{m}_0=0.2654$. After all, the critical value of the second burnout heat flux appears at $\Delta T_{\text{sub}}=91.8\text{ K}$, the critical value of it is $1.8 \times 10^7\text{ W/m}^2$. The measured values of the second burnout heat flux for each subcooling are shown in Fig. 6 by the symbol $\bigcirc$. These values agree well with those obtained from Eq. (8). The relation between the heat flux and the wall superheat at the second burnout regime is determined by substituting the relationship equations, $q_n=79\Delta T_{\text{sat}}^{3.0}$ and $\bar{S}_d/S_w=0.86$, into Eq. (3), that is, from the boiling curve shown by a two-dotted line in Fig. 2.

7. Conclusions

The heat flux was measured at the second burnout point of pool boiling over the range of high subcooling of 30 K to 88 K under atmospheric pressure, and the relation between the heat flux and subcooling was estimated. The main conclusions from the experiment at the second burnout regime may be summarized as follows.

1. The mass flux of condensation into a subcooled liquid from the vapor mass was approximated as a

function of only subcooling from a kinetic theory of molecules.

2. The relationship equation between the heat flux and the mass flux of condensation was obtained, which gave fairly good agreement with the experimental results.

3. According to the relationship equation, the second burnout heat flux does not increase unlimitedly with subcooling, but has a maximum value at a certain subcooling.

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