Subcooled Pool Boiling CHFs on Cylinder due to Transient Heat Input

Jongdoc PARK**, Katsuya FUKUDA*** and Qiusheng LIU***

Detailed understanding of generalized saturated and subcooled pool boiling CHF (Critical Heat Flux) phenomena is very important for the design and the safety assessment such as those in high heat flux cooling systems using subcooled water pool boiling, in the super-conducting magnets cooled by liquid helium and liquid nitrogen, and in the thermal control of microelectronic assemblies for future supercomputers cooled by Fluorinert liquid FC-72. The objective of this work is to clarify the effect of the pressures, subcoolings, and periods on pool boiling CHF, and is to elucidate the generalized phenomena at steady and transient CHF depending on the wettability of boiling liquids. The CHF data were considerably explained by a boiling liquid approach and its property. Photographic observations of the vapor bubble behavior during film boiling transitions were also performed using a high-speed video camera system.

1. Introduction

Energy conversion systems applied in the marine environment require higher performance and efficiency. Extensive researches toward pool boiling characteristics have been widely investigated. However, the correct understanding of its boiling crisis by CHF phenomenon during steady and transient heat transfer as a fundamental database for designing heat generation systems is still need to be clarified.

The typical trend of the CHF values in relation to the heat generation rates shown with period is as follows: the CHF gradually increases with a decrease in period up to the maximum CHF from the steady state one corresponding to the CHF for a period of 20 s, and then the CHF decreases down to the minimum one and again increases with a decrease in period. This trend suggests that there exists another mechanism of CHFs for shorter periods different from the thermal-hydrodynamic instability (HI) model firstly suggested by Kutateladze[1] and Zuber[2]. The CHFs for the shorter periods at which direct or semi-direct transitions to film boiling occurred in transient conduction regime due to a quasi-steadily increasing or increasing heat input for the liquids including water. A direct transition from non-boiling convective regime to film boiling one was reported by Avksentyuk and Mamontova[3] and Kutateladze et al.[4] in liquid metals and wetting liquids as some peculiarities of CHF. However, the mechanism of CHFs for the heat inputs with shorter periods remained unresolved for a long time.

The direct transition from a non-boiling regime such as natural convection and transient conduction regimes to film boiling without nucleate boiling was observed by Sakurai et al.[5]. They carried out the experiments of the CHFs for the heat inputs with various periods on a platinum horizontal cylinder in liquid nitrogen at various pressures, and found that direct transition to film boiling occurred in transient conduction regime. It was assumed that the transitions occurred due to the levitation of liquid on the cylinder surface by the explosive-like heterogeneous spontaneous nucleation (HSN) in originally flooded cavities without the contribution of the active cavities entraining vapors for boiling incipience. All the cavities on the surface that could serve as nucleation sites would initially be flooded since the liquid surface tension is so low that vapor

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are not entrained in surface cavities and there is no dissolved gas in liquid nitrogen except for possible trace amounts of helium, hydrogen and neon. The explosive-like HSN assumed in originally flooded cavities on a horizontal cylinder in the wetting liquid of liquid nitrogen at which heat transfer crisis occurs was first observed without nucleate boiling under natural convection regime at atmospheric pressure due to steadily increasing heat input at a certain HSN surface superheat which is considerably lower than the corresponding the HSN on a flat surface and the homogeneous spontaneous nucleation at surface superheats theoretically obtained.

Recently Chang et al.[6] measured CHF and corresponding surface superheat at which the transition from natural convection regime to film boiling in a pool of FC-87, and also measured minimum film boiling heat flux and corresponding surface superheat. They concluded that the film boiling incipience at the transition point and minimum film boiling at collapse point occur due to the lower limit of HSN in wetting liquid of FC-72 and FC-87 based on the theory of Sakurai et al.[7]. Takahashi et al.[8] has measured the dynamic heat transfer processes due to an exponential heat input for a 1.2 mm diameter horizontal cylinder in a pool of FC-72 at the pressures of 101.3 kPa and 150 kPa. They have assumed that the mechanism of the direct transition from non-boiling regime to film boiling regime is a consequence of the HSN.

The present work is to make clear the transition phenomena to film boiling at steady and transient CHF in non-wetting and wetting liquids. The generalized mechanism for the transitions to film boiling from single-phase conduction or transient conduction and fully or insufficiently developed nucleate boiling due to exponential heat generation rates for wide range of subcoolings and pressures were investigated in water, ethanol and FC-72, adding the photographic approach on the vapor bubble and vapor film behavior on the cylinder surface by using a high-speed video camera.

2. Experimental Apparatus and Method

The schematic diagram of the experimental apparatus is shown in Fig. 1. It mainly consists of a boiling vessel, a test heater inside the vessel, pressurizer, heat generation rate controlling system, measurement and data processing system, and a high-speed video camera. The boiling vessel with inspection windows is made of stainless steel having an inner diameter of 200 mm and a height of 600 mm. The test heater is made of platinum wire having a diameter of 1.0 mm, which is horizontally mounted in the vessel.

The experimental heater is heated electrically by a direct current source controlled by a computer as it is increased in an exponential function with time. The analogue computer computes the instantaneous mean temperature of the cylinder and it cuts off the power supply when the calculated mean temperature reaches a preset value by using the burnout detector. The output voltages of the double bridge circuit, together with the voltage drops across the potential taps of the cylinder and across a standard resistance, were amplified and passed through analog-to-digital (A/D) converters installed in computer. These voltages were simultaneously sampled at a constant time interval that was changed depending on period. The fastest sampling speed of the A/D converter is 5 μs/channel. The average temperature between the potential taps was measured by resistance thermometry using the cylinder itself. The heat generation rate was determined from the current to the cylinder and the voltage difference between potential taps on the cylinder. The surface temperature was obtained by solving the conduction equation in the cylinder under the conditions of the average temperature.
and heat generation rate. The CHF was determined at a start point where the average temperature rapidly increases up to the preset temperature that is lower than the actual burnout temperature of a platinum wire. The uncertainties are estimated to be within ±1 percent in the heat generation rate, ±2 percent in the heat flux and to be within ±1 K in the cylinder surface temperature.

The experiment was carried out as follows. First, the experimental liquids were degassed by keeping it boiling for 30 minutes at least in the auxiliary tank. Vapor was recovered to the pool with a water-cooled condenser. The liquid was fully filled in the boiling vessel with the free surface only in the pressurizer and sub tank. Liquid temperatures in the boiling vessel and in the pressurizer were separately controlled to realize the desired saturated and subcooled conditions. Each of heat flux and surface superheat was calculated by the data processing system with time. The heat input was raised with exponential function, \( Q = Q_0 \exp(\frac{t}{\tau}) \). \( Q_0 \) is initial heat generation rate, W/m\(^3\) and \( \tau \) is time, s. \( \tau \) is period, s: the e-fold time corresponding to heat generation rate with the exponential increasing rates from quasi-steady to rapid ones.

Table 1 shows the experimental condition.

<table>
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<tr>
<th>Table 1 Experimental condition</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>Cylinder</td>
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<tr>
<td>Liquid</td>
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<tr>
<td>Pressure</td>
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<td>Period</td>
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Table 2 shows the properties of each liquid. Generally, highly wetting liquid means it has lower surface tension than that of water, and its contact angle between liquid and heater surface is smaller than that of water, so that it may be easy for a wetting liquid to previously flooded cavities on a cylinder surface. Among three boiling liquids in this experimental, water has highest value of surface tension and FC-72 has lowest one, 17% of water. In the most of the case in FC-72, it is assumed the boiling shows a transition directly to film boiling without passing the nucleate boiling. However the nucleate boiling also occurs for the period of 10 s, which means quasi-steadily increasing heat inputs. Thermally and chemically stable, Fluorinert liquid FC-72 is an ideal choice for low temperature heat transfer applications. The saturation temperature of FC-72 at atmospheric pressure is about 56 degree. It means that it is possible to keep an electronic application under 100 degree of wall temperature, \( T_w \). So, the electronic applications can be cooled with a nucleate boiling, even though there is a rapid increasing heat input due to the pump breakdown etc.

<table>
<thead>
<tr>
<th>Table 2 The properties of each liquid</th>
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<tr>
<td>Properties</td>
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<tr>
<td>Boiling Point (1 atm) [°C]</td>
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<tr>
<td>Liquid Specific Heat [kJ/(kgK)]</td>
</tr>
<tr>
<td>Latent Heat of Vaporization [J/g]</td>
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<tr>
<td>Liquid Thermal Conductivity [W/(mK)]</td>
</tr>
<tr>
<td>Surface Tension [\times 10^{-3}N/m]</td>
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<tr>
<td>Critical Temperature [°C]</td>
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<td>Critical Pressure [MPa]</td>
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3. Experimental Results and Discussion

3.1 Typical boiling heat transfer in water
3.1.1 Heat transfer processes under saturated condition in water

Typical boiling heat transfer processes due to exponentially increasing heat inputs in water are shown in Fig. 2 on a graph of heat flux, \( q \), versus surface superheat, \( \Delta T_{sat} \). The surface superheat \( \Delta T_{sat} \) is defined by the difference between the surface temperature, \( T_s \), of the heater and the saturation temperature, \( T_{sat} \), of liquid corresponding to the system pressure. The steady-state natural convection curve derived by Takeuchi et al.[9], the heat conduction curve derived by Sakurai et al.[10] and the steady-state film boiling curve derived by Sakurai et al.[11] are also shown in the figure for comparison.

The heat transfer processes for periods of 10 s and 0.01 s at a pressure of 101.3 kPa are shown in the
The processes from non-boiling to film boiling are completely different from each other from period to period. It can be found that the processes up to initial boiling heat fluxes, $q_{in}$, are the natural convection regime for period of 10 s, and the heat conduction regime for period of 0.01 s as shown in the figure. It is recognized that the values of initial boiling heat flux, $q_{in}$, increase with a decrease in period, that is, they depend on the increasing rates of heat inputs. When an exponentially increasing heat input is applied to the heater immersed in the pool of water, the heater surface temperature and the heat flux increased. As shown in the figure, the heat transfer processes up to, $q_{in}$, show that heat flux, $q$, for the period of 10 s increases along the natural convection curve and natural convection heat transfer becomes predominant. As the period shortens, the heat conduction becomes predominant in heat transfer compared with the natural convection.

3.1.2 Photographs of vapor film behavior during transition to nucleate boiling in water

Figure 3 is taken using a high-speed video camera for the vapor behavior on a horizontal cylinder during transition to nucleate boiling due to a slowly increasing heat input for a period of 10 s. The photographs in the figure are shown to confirm the assumptions where the corresponding points on the heat transfer process curve at the points of 3(a) to 3(f) are shown in Fig.2 with a solid line. Figure 3(a) is the onset of boiling and it can be seen with a few initial vapor bubbles. Figures 3(b) and 3(c) are the photographs after the time passage of 6.8 s and 12.8 s from point (a), respectively. It takes a long time for the vapor bubbles to spread to the whole surface of

![Fig. 3 Vapor film behavior during transition to fully developed nucleate boiling (FDNB) for a period of 10 s at atmospheric pressure in saturated water.](image)

![Fig. 4 Vapor film behavior during semi-direct transition to film boiling for a period of 0.01 s at atmospheric pressure in saturated water.](image)
the test heater as shown in the figure. The vapor bubbles around the heater occur from active cavities of entrained vapor that cause the increase of heat flux. After incipient boiling at a point which corresponds to the $q_{\text{in}}$, the surface superheat, $\Delta T_{\text{sat}}$, does not change so much with an increase in heat input. As shown in Fig. 3(d), the small bubble nucleus commences to coalesce in the nucleate boiling region to form coalesced bubbles. The detached coalesced bubbles continuously increase in size with increases in the heat flux at the points of 3(e) to 3(f).

3.1.3 Photographs of vapor film behavior during semi-direct transition to film boiling in water

Figure 4 shows the semi-direct transition from transient conduction regime to film boiling due to a rapidly increasing heat input for the period of 0.01 s. The CHF almost agrees with the quasi-steady-state CHF for the period of 10 s. The mechanism of semi-direct transition from transient conduction regime to film boiling was not solved for a long time. Sakurai et al.[5] assumed that the mechanism of semi-direct transition to film boiling with slight nucleate boiling from active cavities occurs finally due to the HSN at around the lower limit of HSN surface superheat in originally flooded cavities; the lower limit value was measured under the condition with pre-pressurization for a quasi-steadily increasing heat inputs. Figures 4(a) to 4(f) are shown to confirm their process. The corresponding points on the heat transfer curve on the $q$ versus $\Delta T_{\text{sat}}$ graph for each photograph are shown in Fig. 2 with a dashed line. Figure 4(a) is the photograph at point 4(a), which is the onset of boiling. It shows the cylinder in transient conduction regime with a few initial vapor bubbles. The time, $t$, beside each photograph shows the elapsed time after the time of first photograph, Fig. 4(a). Figure 4(b) is the photograph after a time passage of 2 ms from point (a). Figures 4(b), 4(c) and 4(d) show vapor bubbles around the cylinder occurred from active cavities of entrained vapor which cause the rapid increase of heat flux without the detachment of vapor bubbles. The heat flux for Fig. 4(d) is around the CHF. A large vapor film covers the cylinder including all the vapor bubbles from active cavities as shown in Fig. 4(d). As seen in Fig. 4(e), the large vapor film with the Taylor unstable wave on the top of the vapor film moves upward with a decrease in heat flux and an increase in surface superheat. After that, the large vapor bubbles are separated from the vapor film with the approximate interval of the most dangerous Taylor wave length, and levitate in the liquid as seen in Fig. 4(f). The heat flux approaches around minimum film boiling heat flux and then increases along the steady-state film boiling heat flux with an increase in surface superheat.

3.2 Direct transition phenomenon in ethanol

Figure 5 shows the transient phenomenon on a graph of heat flux, $q$, versus surface superheat, $\Delta T_{\text{sat}}$, at a pressure of 101.3 kPa and a period of 0.1 s in saturated ethanol. The surface superheat $\Delta T_{\text{sat}}$ is defined by the difference between the surface temperature, $T_w$, of the heater and the saturation temperature, $T_{\text{sat}}$, of liquid corresponding to the system pressure. The heat conduction curve derived by Sakurai et al.[10] and the steady-state film boiling curve derived by Sakurai et al.[11], are also shown in the figure for comparison. The boiling process caused by an exponentially increasing heat input with a period of 0.1 s at atmospheric pressure, shows that the $q$ value increases along the natural convection heat transfer curve, and the boiling occurs at a surface superheat point of 100 K, and then shows a transition directly to film boiling.
without passing the nucleate boiling. The initial boiling temperature gradually decreased with an increase in system pressure based on experimental data. It is considered that the direct boiling transition on the heater surface from non-boiling to film boiling is due to the heterogeneous spontaneous nucleation (HSN) in previously flooded cavities on heater surface as suggested by Sakurai et al.[5].

Figure 6 gives a series of subsequent photographs from the moment of onset of a vapor phase to film boiling on a surface at a pressure of 101.3 kPa in saturated ethanol. Figure 6(a) is the onset of boiling on the cylinder. The figure 6(b) taken at 1 ms after the first one shows a vapor tube due to the explosive-like HSN in flooded cavities, and it covers the whole cylinder surface by the large vapor tube. Figure 6(c) taken at 2 ms after the first one shows thick vapor film concentrically covering the cylinder. The vapor bubbles are very rapidly growing and completely covering the surface of the cylinder within just a few milliseconds. The temperature difference of the surface superheat between corresponding to Figs. 6(a) to 6(c) is almost the same. Figure 6(d) taken at 15 ms after the first one shows that the vapor bubbles collapse from the boiling initiation bubbles. Then, large vapor bubbles are broken away from the large vapor film by buoyancy force and move upward as shown in Fig. 6(e). After detachment of the large vapor bubbles, solid-liquid contacts occurs, and then new thin vapor film with the Taylor unstable wave on the upper part of the vapor-liquid interface covering the cylinder is formed by the explosive-like HSN on the places of solid-liquid contact and thin film boiling. At this moment the surface temperature starts increasing rapidly as a result of heat transfer deterioration. As shown in figure 6(f), the behavior of vapor-liquid interface in film boiling on the cylinder similar to that for steady-state film boiling on the cylinder is clearly observed after the detachment of large vapor bubbles.

3.3 Typical boiling heat transfer in FC-72
3.3.1 Heat transfer processes up to CHFs

Heat transfer processes during transitions to fully-developed nucleate boiling or to film boiling at atmospheric pressure in saturated FC-72 are shown in the Fig. 7. It seems that the heat transfer processes to film boiling that are completely different from each other due to the exponential period. For the period of 0.02 s, the processes up to initial boiling heat fluxes, $q_{in}$, is the heat conduction...
regime derived by Sakurai et al.\[10\]. It is considered that the direct boiling transition from non-boiling to film boiling is due to the heterogeneous spontaneous nucleation (HSN) as mentioned before. For the period of 10 s, however, after the occurrence of initial boiling, the nucleate boiling occurs from the cavities of entrained vapor that are formed after detachment of vapor bubbles with a slight decrease in surface superheat which prevents the growth of the HSN.

3.3.2 Photograph studies in vapor behavior

Figure 8 shows the photographs of transient boiling behavior taken by a high-speed video camera at the corresponding points shown in Fig. 7. The vapor bubbles are rapidly growing and surrounding the cylinder surface. The rapid growth of vapor bubbles is due to heterogeneous spontaneous nucleation (HSN) within the flooded cavities of cylinder. As shown in the figure, the vapor bubbles covered almost all the heater surface within just a few milli second. It is seen that the vapor bubbles are separated from the cylinder surface. Figure 8(e) is the photograph of the time at which 15 ms elapsed from point (a). The film boiling appears after the departure of vapor bubbles. Figure 8(f) is the photograph after the time passage of 42 ms from point (a) and is the stable film boiling after passing the point (e).

Figure 9 shows the photographs for typical vapor film and vapor bubble behaviors in the transition to developed nucleate boiling corresponding points shown in Fig. 7. The large vapor bubbles are rapidly growing and surrounding the cylinder surface, and the cylinder is almost fully covered with the vapor bubbles as shown in the Fig. 9(2). This vapor film behavior that are rapidly growing and covering the heater surface during boiling initiation could never be seen in the water experiment with quasi-steadily increasing exponential heat input. As seen in Fig. 9(3), the nucleate boiling occurs from the cavities of entrained vapor that are formed after detachment of vapor bubbles with a slight decrease in surface superheat which prevents the growth of the HSN. If the detachment of vapor bubbles without decreasing in average surface superheat is realized, the direct or semi-direct transition occurs as in the case of rapidly increasing in heat input mentioned.
4. Conclusions

The vapor behavior on the horizontal cylinder during the transition from natural convection and transient conduction regimes to film boiling in water and highly wetting liquids such as ethanol and FC-72 due to various exponentially increasing heat inputs including a quasi-steadily increasing heat input to a rapid increasing one was examined by the photographs taken using a high-speed video camera.

In the case of the highly wetting liquids, the initial boiling behavior until transition to fully developed nucleate boiling was just similar to that of the direct transition to film boiling. This vapor film behavior that was rapidly growing and covering the heater surface during initial boiling could never be seen in the water experiment with a quasi-steadily increasing exponential heat input. It was confirmed that the initial boiling behavior is significantly affected by the property and the wettability of the liquid. For boiling processes with shorter periods, the direct or semi-direct transition to film boiling occurred with an explosive transition from non-boiling to boiling. We concluded that the direct or semi-direct transition to film boiling comes from the detachment of vapor bubbles without decreasing of surface superheat.

References