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Critical Heat Flux Phenomena Depending on Pre-pressurization in Transient Heat Input

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Abstract. The critical heat flux (CHF) levels that occurred due to exponential heat inputs for varying periods to a 1.0-mm diameter horizontal cylinder immersed in various liquids were measured to develop an extended database on the effect of various pressures and subcoolings by photographic study. Two main mechanisms of CHF were found. One mechanism is due to the time lag of the hydrodynamic instability (HI) which starts at steady-state CHF upon fully developed nucleate boiling, and the other mechanism is due to the explosive process of heterogeneous spontaneous nucleation (HSN) which occurs at a certain HSN superheat in originally flooded cavities on the cylinder surface. The incipience of boiling processes was completely different depending on pre-pressurization. Also, the dependence of pre-pressure in transient CHFs changed due to the wettability of boiling liquids. The objective of this work is to clarify the transient CHF phenomena due to HI or HSN by photographic.

INTRODUCTION

Understanding of transient boiling phenomena caused by increasing heat inputs in subcooled water at high pressures is necessary to predict correctly a design-based severe accident due to a power burst in a water-cooled nuclear reactor.

The anomalous trend of CHF which increases, then decreases and again increases with decreasing of period, has been reported in previous papers (Sakurai et al. (2002)). Two main mechanisms of CHF exist depending on the exponential periods. One is due to the time lag of the hydrodynamic instability (HI) which starts at steady-state CHF on fully developed nucleate boiling, and the other one is due to the explosive-like heterogeneous spontaneous nucleation (HSN) which occurs at a certain HSN superheat in originally flooded cavities on a cylinder surface. Recently, the pool boiling CHF for various liquids using 1.0 mm diameter horizontal cylinder of platinum was measured to investigate on the boiling behavior of transient phenomena (Park et al. (2010)). It was confirmed that the vapor film behavior during transition to fully developed nucleate boiling or direct transition at the CHF to film boiling was significantly affected by the property and the wettability of the liquids.

The role of spontaneous nucleation in originally flooded cavities on the cylinder surface called HSN is dealt with in this paper. The HSN phenomenon occurs when a new phase appears at an interface or a boundary rather than in the bulk fluid similar to the homogeneous spontaneous nucleation (Stralen et al. (1979)). It has been clarified by Sakurai

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et al. (1993) that CHFs due to steady and transient heat generation rates on the cylinder surface at certain conditions in water are determined by the explosive-like heterogeneous spontaneous nucleation (HSN): it occurs at the HSN surface superheat in originally flooded cavities on the cylinder surface. The HSN phenomenon was observed on the cylinder surface in previously degassed water before each experimental run by high pressure of 5 MPa for a while: the incipience of boiling from active cavities previously entraining vapor was replaced to that resulting from the HSN in originally flooded cavies.

The objective of this work is to clarify an effect of the pre-pressurization at a pool boiling CHF, and to make clear the generalized phenomena at transient CHF depending on the wettability of boiling liquids. As a continuation of previous work, boiling heat transfer processes on a horizontal cylinder in water (dealt with non-wetting liquid here) or highly wetting liquid such as FC-72 due to exponentially increasing heat input with various periods were measured for saturated liquids at atmospheric pressure. The CHF data were considerably explained by a boiling liquid approach and an empirical correlation was derived.

EXPERIMENT APPARATUS AND METHOD

The schematic diagram of the experimental apparatus is shown in Fig. 1. The experimental apparatus consists of a boiling vessel, a horizontal cylinder of experimental heater, a pressurizer, a control device of heat generation rate, a data measurement and processing system.

The cylinder 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 $5\mu s$/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.

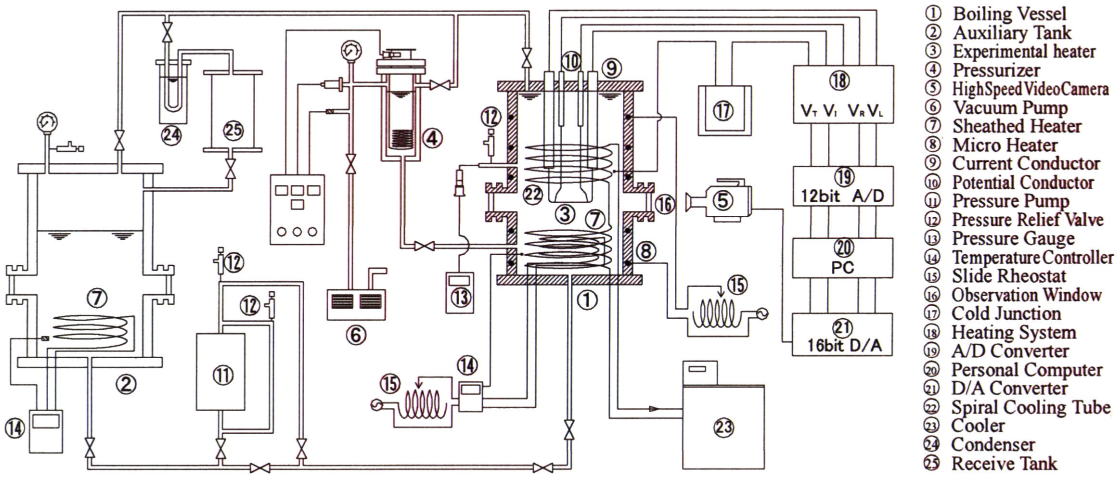

FIGURE 1. Schematic diagram of experimental apparatus.

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, $Q=Q_0\exp(t/\tau)$. Q_0 is initial heat generation rate, W/m^3 and t is time, s. τ is period, s: the e-fold time corresponding to heat generation rate with the exponential increasing rates from quasi-steady to rapid ones.

EXPERIMENTAL RESULTS AND DISCUSSION

Effect of pre-pressurization on the heat transfer processes in water

Pre-pressurization was also taken consider to a large potential of nucleation sites dissipation on the surface cavities then assumed trigger a spontaneous nucleation of boiling process. According to a series of experiment under atmospheric pressure, the surface superheat at incipience of boiling, ΔT_{in}, for lower pre-pressures showed the effect of pre-pressurization due to active cavities on cylinder surface. But the constant ΔT_{in} values were measured for higher pre-pressures (Sakurai et al. (2000)).

The heat transfer processes with two kinds of pre-pressurization with the exponential heat inputs for the period τ=100 ms (means highly increasing one) at atmospheric pressure for saturated condition in water are shown on the graph of heat flux q versus surface superheat ΔT_{sat} in Fig. 2. It can be found that the incipience of boiling processes and boiling curves are completely different from each other depending on pressurization. In the case of pre-pressurized one, it shows the transition from non-boiling to film boiling directly caused by HSN surface superheat. By the effect of pre-pressurization, the boiling incipience mechanism was completely changed because it became previously degassed water before the experiment run. Photographs of vapor film behavior will be shown later. The surface superheat at incipience of boiling for pre-pressure of none and 5 MPa results the ΔT_{in} of 20 K and 80 K, respectively.

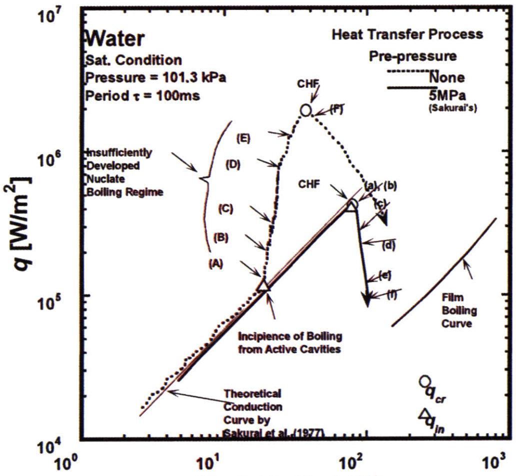

FIGURE 2. Transitions from non-boiling to insufficiently developed nucleate boiling (IDNB) or film boiling caused by exponential heat inputs for a period τ=100 ms in saturated water. Photographs were shown in **FIGURE 4**.

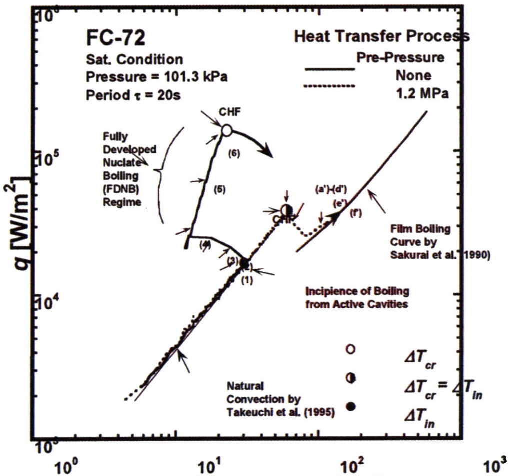

FIGURE 3. Transitions from non-boiling to fully-developed nucleate boiling (FDNB) or film boiling caused by exponential heat inputs for a period τ=20 s in saturated FC-72. Photographs were shown in **FIGURE 5**.

Transition processes to nucleate boiling or to direct film boiling in FC-72

Figure 3 shows the heat transfer processes with and without pre-pressurization for the period τ=20 s (means quasi-steadily increasing one) at atmospheric pressure in saturated FC-72. The boiling curve without pre-pressurization is shown with a solid line: heat flux, q, increases along the natural convection curve at first and after the incipience of boiling at a surface superheat of 30 K, the surface superheat rapidly decreases, and the transition to fully developed nucleate boiling occurs and reaches the CHF point. On the other hand, in the case of pre-pressurized one as shown with a dashed line, the CHF point is due to the direct transition from single-phase conduction regime to film boiling; the value ΔT_{in} is equal to ΔT_{cr}. The boiling occurs at a surface superheat point of 60 K, which is higher than that of none pre-pressured one. It is considered that the direct boiling transitions occur due to the levitation of liquid on the cylinder surface by the explosive-like HSN in originally flooded cavities without contribution of the active cavities entraining vapors pressures (Fukuda et al. (1995), Sakurai et al. (2000)).

Here, it turns out that both superheats at incipience of boiling completely changes because of pre-pressurization. That is, it becomes there is no active cavities entraining vapor by applying pre-pressure, and it is hard for incipience of boiling. Moreover, the difference of the CHFs on each condition has come out, and it is important for the database in the design of various kinds of heat flux apparatus.

By the way, the transition processes can be classified into three principal groups. The first group is, the CHF occurred through a nucleate boiling as shown in the Figs. 2 & 3. And the direct transition to film boiling without nucleate boiling belongs to the second group as shown in the Fig. 2 & 3 in the case of pre-pressured one. Finally there exists the third group for intermediate one between first and second groups.

Photographs of vapor film behavior in water and FC-72

In this section, the explosive boiling due to HSN is dealt with, instead of the typical nucleate boiling caused by active cavities. Figure 4a and 4b show the photographs for with a period of 100 ms at a pressure of 101.3 kPa at the corresponding points shown in Fig. 2 in water. Figure 4a shows the transition from transient conduction regime to insufficiently developed nucleate boiling (IDNB) under non-pre-pressurization condition. The mechanism of semi-direct transition from transient conduction regime to film boiling was not solved for a long time. Sakurai et al. (1993) 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. Figure 4a(A) is the photograph at point 4a(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. 4a(A). Figure 4a(B) is the photograph after a time passage of 32 ms from point (A). Figures 4a(B), 4a(C) and 4a(D) show vapor bubbles around the cylinder occurred from active cavities of entrained vapor which cause the rapid increase of heat flux with the detachment of vapor bubbles. The heat flux for Fig. 4a(F) is around the CHF. Figure 4b is the photograph at point (a), which is the onset of boiling. Figure 4(b) is the photograph after a time passage of 5 ms from point (a). After the onset of boiling as photo no. (a) and (b), it shows a large spherical vapor bubble due to the HSN which is formed rapidly within 5 ms. After that, it covers the whole cylinder surface with large vapor tube. This is typical behavior of direct transition due to the HSN.

On the other hand, Figure 5a and 5b show the photographs for the pre-pressurization at the corresponding points shown in Fig. 3 in FC-72. Figure 5a shows the photographs for typical vapor film and vapor bubble behaviors in the transition to developed nucleate boiling under non-pre-pressurization condition. 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. 5a(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. 5a(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 before. Figure 5b(a') is the onset of boiling on the cylinder. The (b') taken at 1 ms after the first one shows a vapor tube due to the explosive-like HSN in flooded cavities, and it

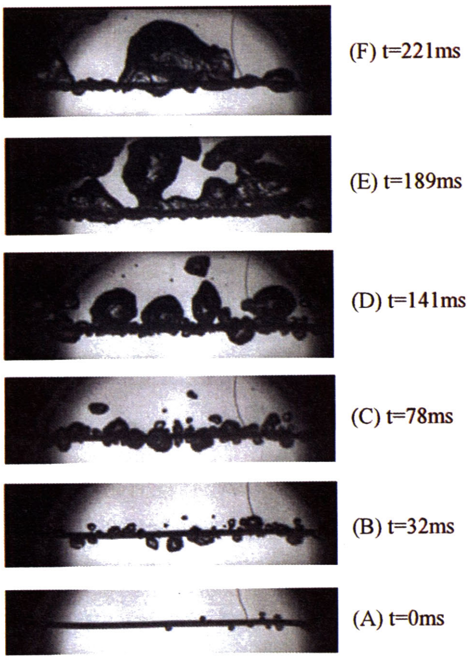

FIGURE 4a. Vapor film behavior during transition to IDNB at atmospheric pressure in saturated water with None-pre-pressurization.

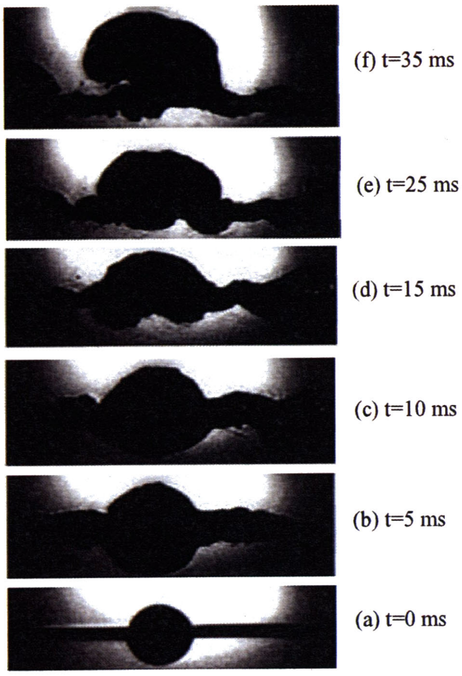

FIGURE 4b. Vapor film behavior during direct transition to film boiling at atmospheric pressure in saturated water with pre-pressurization (Sakurai et al. (2000)).

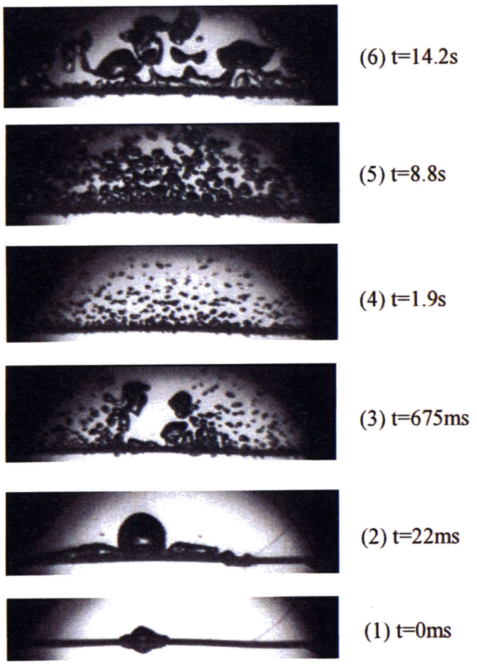

FIGURE 5a. Vapor film behavior during transition to FDNB at atmospheric pressure in saturated FC-72 with None-pre-pressurization.

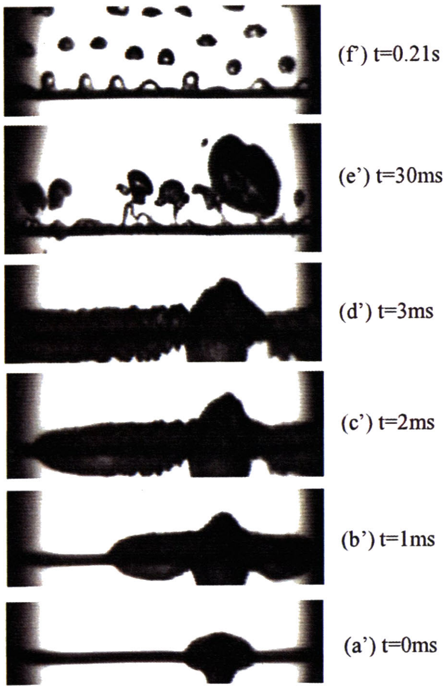

FIGURE 5b. Vapor film behavior during direct transition to film boiling at atmospheric pressure in saturated FC-72 with pre-pressurization.

covers the whole cylinder surface by the large vapor tube as shown (c')-(d'). The (e') show 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. The temperature difference of the surface superheat between corresponding to Figs. (a') to (d') is almost the same. 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 (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.

CONCLUSIONS

The pool boiling CHFs were investigated to clarify the generalized phenomena of transition to film boiling at transient condition.

- The incipience of boiling processes was completely different depending on the pre-pressurization and the wettability of boiling liquids.
- By the effect of pre-pressurization, the boiling incipience mechanism was replaced from that by active cavities entraining vapor to that by the HSN in originally flooded cavies.
- The direct transition without nucleate boiling to film boiling was explained by the HSN.

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