About Pool Boiling CHF in Different Wettability Liquids

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Abstract

This study deals with critical heat flux that occurs in boiling heat transfer while transient heat input as it increased in a exponential function with time in a pool of water and well wetting liquid, ethanol. The boiling heat transfer characteristics and CHFs were measured using a 1.0 mm diameter horizontal cylinder for wide range of pressures and subcoolings, with the photographic observations on the vapor bubble behavior by using a high-speed video camera. It was confirmed that CHFs changed systematically depending on experimental conditions. The quasi-steady-state CHFs measured were divided into two mechanisms for lower and higher subcooling resulting from HI or HSN. The dependency of HSN in the high subcooling was found remarkably in wetting liquid. Typical trends of the transient CHFs were clarified to three groups corresponding to time constant, periods; the first, second and third groups of CHF were for longer periods, for shorter and for intermediate ones.

Keywords: CHF, Pool boiling, film boiling, horizontal cylinder

1. Introduction

As known well, the CHFs change systematically depending on experimental conditions. The authors have reported the CHFs measured are classified into two mechanisms such as HI and HSN as a typical trend. Many aspects of saturated and subcooled pool boiling CHF in the liquids have been investigated by many researchers for pressure, subcooling, test heater configurations, surface conditions, thermal properties, etc., assuming a CHF model mainly based on a kind of hydrodynamic instability (HI) first suggested by Kutateladze(1) and Zuber(2). The some researchers pointed out that a few key aspects in the complex CHF phenomena observed still remain unsolved until now. On the other hand, recently the pool boiling CHF for a horizontal cylinder in water and wetting liquids were measured for comparatively wide range of pressures at saturated condition by the authors(3): it was confirmed that boiling heat transfer processes were completely different from each other depending on the experimental liquids, and the CHFs measured were divided into two mechanisms for longer and shorter period resulting from hydrodynamic instability (HI) model and explosive-like heterogeneous spontaneous nucleation (HSN) model respectively.

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(4). It has been clarified by Sakurai et al. (5) that steady-state and transient CHFs due to exponential increasing heat generation rates shown with period on the cylinder surface at certain conditions are determined by the explosive-like HSN: it occurs at the HSN surface superheat in originally flooded cavities on the cylinder surface. The heat transfer crisis at the CHF assumed to occur resulting from the explosive-like HSN in the fully developed nucleation regime has been observed in a pool of highly subcooled water at higher pressures: the CHF was significantly lower than the value derived from the CHF correlation representing the CHF

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resulting from the HI. Besides, a direct transition from a non-boiling regime such as natural convection and transient conduction regimes to film boiling without nucleate boiling occurred due to the HSN in a pool of wetting liquids was observed by Sakurai et al. [(6)-(7)]. The direct transition was reported by Avksentyuk and Mamontova[(8)] and Kutateladze et al. [(9)] in liquid metals and wetting liquids as some peculiarities of CHF. However, the mechanism of CHFs for the transient heat inputs with shorter periods remained unresolved for a long time. Sakurai et al. have clarified the phenomenon due to HSN in detail. It was assumed that the transitions occurred due to the levitation of liquid on the cylinder surface by the explosive-like 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 are not entrained in surface cavities.

Recently, the heat transfer processes and CHFs in a pool of FC-72 were reviewed by Ohya et al. [(10)] for subcoolings of 0 to 35 K at atmospheric pressure. They have assumed that the direct transition would occur due to the instantaneous levitation of the liquid by explosive initiation of HSN. Chang et al. [(11)] performed to investigate the pool boiling nucleation behavior in saturated FC-72 and FC-87 at atmospheric pressure. They confirmed that the surface superheats at the transition from natural convection to film boiling and minimum film boiling superheat at collapse point agreed with each other. They concluded that the corresponding superheats occur due to the lower limit of HSN based upon the theory of Sakurai et al. [(12)-(13)].

The purpose of present work is to make clear the transition phenomena to film boiling at steady and transient CHFs in non-wetting and wetting liquids. The CHFs were measured with a platinum wire due to exponential heat generation rate for wide range of subcoolings and pressures in a pool of water and highly wetting liquids such as ethanol, with the photographic approach on the vapor bubble and vapor film behavior on the cylinder surface by using a high-speed video camera system. In this paper, it will be shown that the CHFs change systematically depending on experimental conditions, and the generalized CHF mechanisms will be suggested that can be applied in wide range of liquids.

2. Experimental apparatus and method

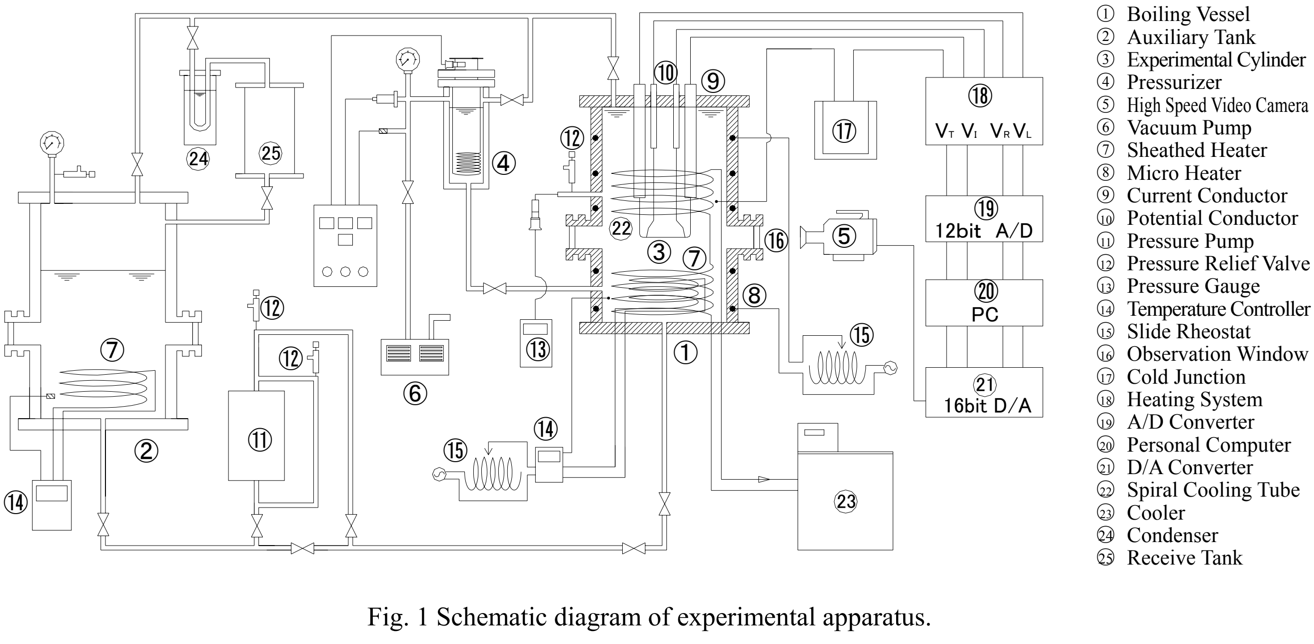

Fig. 1 Schematic diagram of experimental apparatus.

2.1 Pool boiling apparatus

The experimental apparatus consists of a boiling vessel, a cylinder of experimental wire, a pressurizer, auxiliary tank for degassing, coolant circulation device (cooler), a control device of heat generation rate, a data measurement and 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. It is designed to use at pressure up to 2 MPa. Two current conductors and two potential conductors which support the cylinder are mounted at the upper side of the vessel. The effective length on the cylinder between the potential taps is about 31 mm. The cylinder is 1.0-mm diameter of platinum wire, which is horizontally immersed in the vessel. The cylinder diameter is determined after the diameter dependency reported by Lienhard et al. (14) showing with the prediction curve for cylinder. As shown in the curve, non-dimensional length L' ($= L/[\sigma / g(\rho_l - \rho_v)]^{1/2}$) becomes the diameter that is considered to be Zuber's infinite horizontal flat plate.

2.2 Method and procedure

In this experiment, it was used a heat generation rate control system, which was improved on that of Sakurai et al. (15). The block diagram of the heating device for the cylinder (test heater), and the measuring and data processing system are shown in Fig. 2. The cylinder was heated electrically by a direct current source controlled by a computer as it was increased in an exponential function with time. It is possible the power source is shut down rapidly at a point which the surface temperature of cylinder reached to preset value. 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. The average temperature of cylinder 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 that the measured average temperature rapidly increased up to the preset temperature lower than the actual burnout temperature of a cylinder by using the burnout detector.

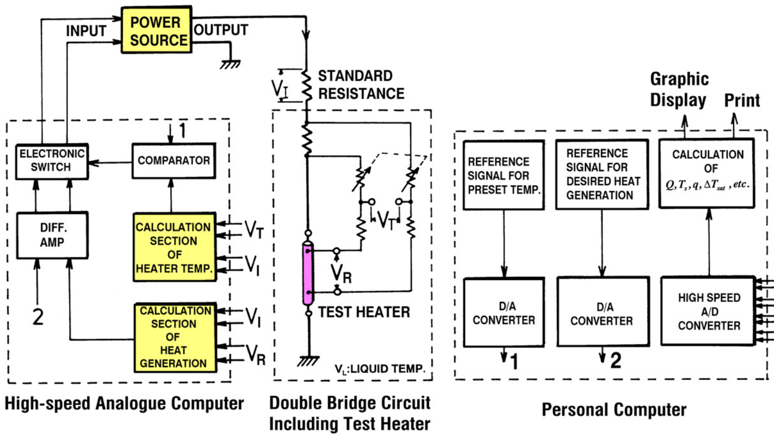

Fig. 2 Block diagram of the heating device for the test heater, and the measuring and data processing system.

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. The heat input was raised with exponential function, $Q=Q_0 exp(t/\tau)$. Heat flux and surface temperature of the heater was measured by the data processing system with time.

2.3 Experimental condition

Table 1 shows the experimental condition for wide range of pressures, subcoolings and periods. Period, τ is defined by a heat generation rate increased by exponential function: the e-fold time corresponding to heat generation rate with the exponential increasing rates from quasi-steady to rapid ones.

Table 2 presents the properties at normal condition in water and ethanol for comparison. As seen in the table, when the physical-properties of liquids are compared with each other, it is shown the value becomes low with the order of water and ethanol. Generally, highly wetting liquid means that it has lower surface tension and its contact angle between liquid and cylinder surface is smaller than that of water, and it is easy to be originally flooded cavities with liquid, for example, ethanol, liquid nitrogen and FC liquids, etc. Ethanol has very low value of surface tension than water. In the case of ethanol, it is assumed that the boiling transitions tend to occur due to the explosive-like HSN in originally flooded cavities without the contribution of the active cavities entraining vapors for boiling incipience. The vapor behavior at initial boiling due to the HSN is shown later: it is considerably different from that due to active cavities. The surface tension has an effect on wettability between cylinder surface and liquid, and it also fixes the number of active cavities. So it can be confirmed the different boiling phenomena.

Table 1 Experimental condition

Items	Contents
Cylinder	Platinum wire
Liquid	Water and Ethanol
Pressure	101.3-1572 kPa
Subcooling	0-160 K
Period	5 ms-20 s

Table 2 Comparison of properties for liquids

Properties	Water	Ethanol
Boiling Point @ 1atm [ºC]	100	78
Liquid Specific Heat [kJ/(kg·K)]	4.19	2.42
Latent Heat of Vaporization [J/g]	2257	855
Liquid Thermal Conductivity [W/(m·K)]	0.61	0.17
Surface Tension [$\times10^{-3}$N/m]	72	21
Critical Temperature [ºC]	374	243
Critical Pressure [MPa]	22	6.4

3. Results and discussion

3.1 Heat transfer processes under saturated condition in liquids with different wettability

Typical boiling heat transfer processes due to exponentially increasing heat inputs are shown in Fig. 3 on a graph of heat flux, q, versus surface superheat, ΔT_{sat}. The figure shows the heat transfer processes for typical two types of liquid, which represent non-wetting liquid (water) and wetting one (ethanol). The transition processes from non-boiling to film boiling or to fully-developed nucleate boiling (FDNB) are completely different from each other depending on liquids and pressures. It can be found that the processes up to boiling initiation heat fluxes, q_{in}, increase along the natural convection curves. Also the transition superheats of boiling incipience are quite different from each other due to experimental conditions.

In the case of water, it is assumed that the incipience of boiling occurs from active cavities entraining vapor that cause the rapid increase of heat flux. Water has higher surface tension than that of ethanol as shown before. Therefore it is easy to form the contribution of the active cavities. Then it reaches the CHF point resulting from HI model as a

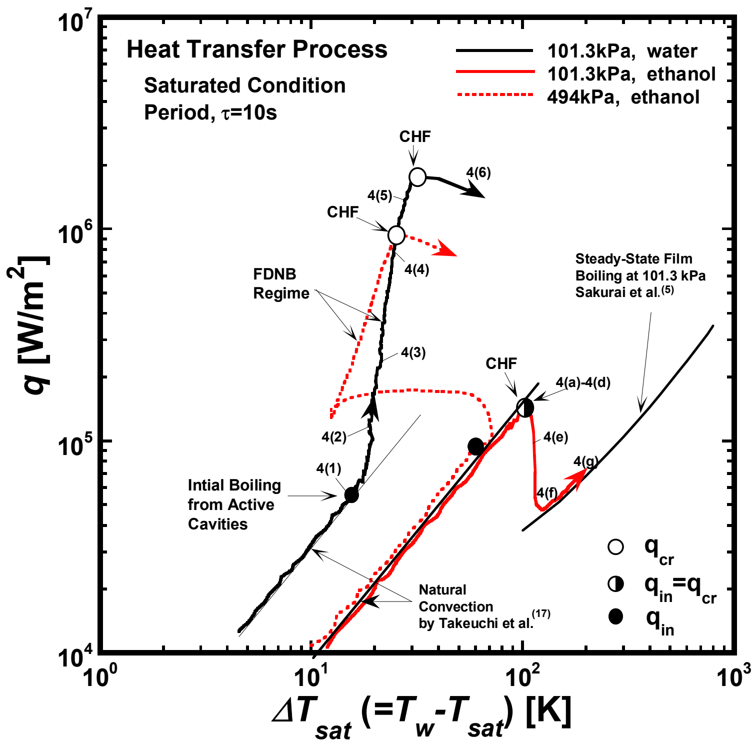

Fig. 3 Transitions from non-boiling to film boiling or to FDNB in saturated liquids at pressures of 101.3 and 494 kPa.

typical case. On the other hand, the red solid line shows the heat transfer process for ethanol at a same pressure of water. The curve shows completely different process. The initiation of boiling occurs at a surface superheat point of 100 K, which is much higher than that in the case of water, and then shows a direct transition to film boiling. The CHF value, q_{cr} is equal to q_{in}. It is considered that the direct boiling transition on cylinder surface from non-boiling to film boiling is due to the HSN in previously flooded cavities as suggested by Sakurai et al.[(6), (7), (16)]. Besides, the transition process at 494 kPa in ethanol shows a quite different boiling curve. The heat flux, q, increases along the natural convection curve at first and after the occurrence of initial boiling at a surface superheat of 60 K, the surface superheat rapidly decreases, and the transition to FDNB occurs and reaches the CHF point, q_{cr}. This fact means that it tends to occur the nucleate boiling under high pressure that is why the physical trend of boiling and surface energy is changed.

3.2 Photographic studies in vapor behavior at transitions to film boiling

Photographs in Fig. 4 are those of frames by high-speed video camera for the vapor film behavior on a horizontal cylinder in water and ethanol at a pressure of 101.3 kPa with 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 are shown in Fig. 3. It can be seen that the transition phenomenon are completely different from each other. In the case of water first, Fig. 4(1) is the onset of boiling and it can be seen with a few initial vapor bubbles due to active cavities on cylinder surface. It takes a long time for the vapor bubbles to spread to the whole surface of cylinder as shown in a series of subsequent photographs. The mechanism of transition to film boiling with fully-developed nucleate boiling (FDNB) from active cavities entrained vapor for the long period occurs finally

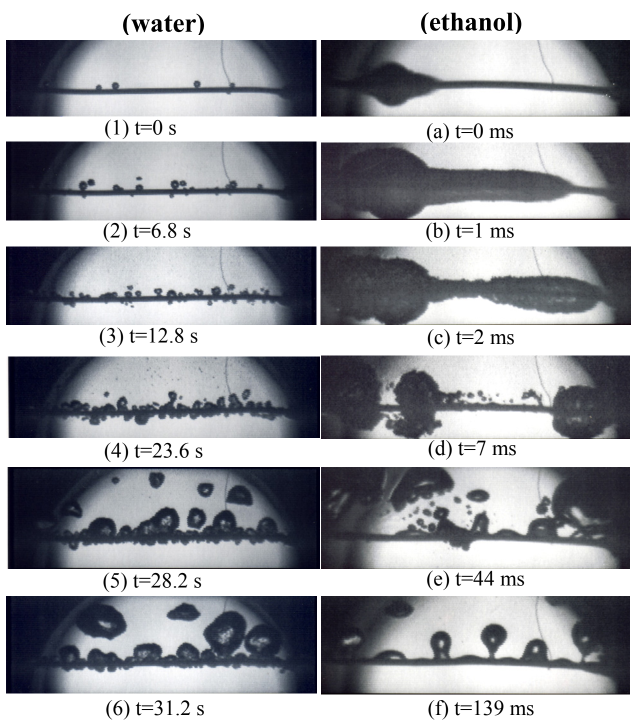

Fig. 4 Vapor film behavior in saturated water and ethanol at 101.3 kPa with the period of 10s.

due to the HI suggested by Kutateladze[1] and Zuber[2]. On the other hand, Fig. 4(a) is the onset of boiling on the cylinder in ethanol. It covers the whole cylinder surface by the large vapor tube within just a few milliseconds. After detachment of the large vapor bubbles, new thin vapor film is formed by the explosive-like HSN on the places of solid-liquid contact and thin film boiling. As shown in the figure, the vapor behavior at initial boiling due to the HSN that is considerably different from that due to active cavities.

3.3 Steady-state critical heat fluxes (CHFs)

In this experiments, heat transfer processes for the periods longer than 10 s were considered as quasi-steady-state ones because the non-boiling region agreed with natural convection heat transfer, and all CHFs measured for the heat inputs with periods longer than 10 s were almost the same.

3.3.1 CHFs in water as a typical trend

The saturated and subcooled pool boiling CHF for a horizontal cylinder in water were measured for comparatively wide ranges of pressure and subcooling reported by Sakurai et al.[12]. The CHFs measured were divided into two groups for lower and higher subcooling at a pressure as a typical trend with the two different mechanisms. A large part of the transition processes to film boiling at CHF highly subcooled liquids at high pressure was not explained by the mechanism of critical heat flux based on the hydrodynamic instability (HI) model. Another mechanism assumed is that the transition occurs due to the explosive-like heterogeneous spontaneous nucleation (HSN) in originally flooded cavities on the cylinder surface. The measured all transition processes for wide ranges of subcooling and pressure in the liquid due to steady and transient conditions were explained by the HI and HSN models for lower and higher subcooling, respectively.

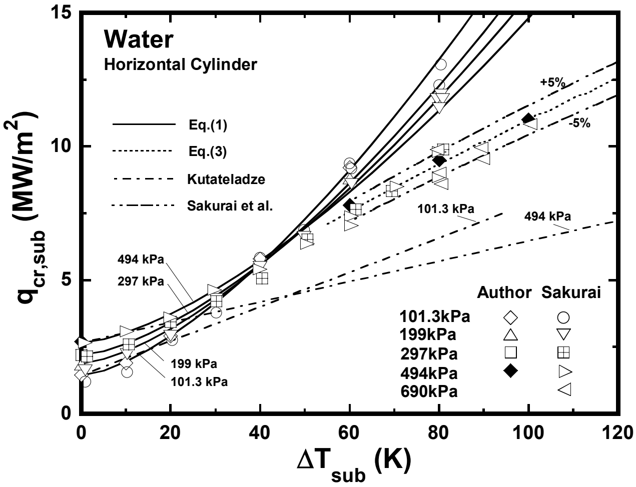

Fig. 5 Comparison of prediction with $q_{cr,sub}$ for subcooling with pressure as a parameter in water using Eqs.(1), (3), Kutateladze's correlation and Sakurai's data.

From this opinion, Sakurai et al. considered that there exist the non-linear effect of subcoolings in the CHF based on HI from experimental results for wide range of subcoolings and pressures in various liquids. Equation (1) is derived by modifying the Kutateladze's correlation taking into account the non-linear effect of high liquid subcoolings on the q_{cr}, and shown in Fig. 5 by solid line.

$$q_{cr,sub} = q_{cr,sat}\left[1 + K_2(\rho_l/\rho_v)^{0.69}(C_{pl}\Delta T_{sub}/L)^{1.5}\right] \quad (1)$$

$$\text{where,} \quad q_{cr,sat} = K_1 L\rho_v\left[\sigma g(\rho_l - \rho_v)/\rho_v^2\right]^{0.25} \quad (2)$$

$$K_1 = 0.17, \quad K_2 = 0.40(L')^{-0.6},$$

$$L' = \frac{D/2}{\sqrt{\sigma / g(\rho_l - \rho_v)}}$$

$$q_{cr,sub} = K_3 \Delta T_{sub}^{\ 0.73} \quad (3)$$

3.3.2 CHFs in well wetting liquid ethanol

Figure 6 shows steady-state CHF data related to subcoolings with pressure as a parameter in a pool of ethanol with corresponding CHF curves obtained by empirical equations, Eqs. (1) and (4) for comparison. As shown in the figure, the CHFs expected by the correlation based on the HI exist in a very narrow range of low subcooling near saturated condition, and they gradually increase with an increase in subcooling. It also seems the CHFs for high subcoolings are independent of pressure. As mentioned before, Sakurai et al. [(7), (16)] has reported that CHF data obtained for high subcoolings at high pressures in a pool of water are due to the HSN. Also here, the empirical equation of CHF for high subcoolings is derived Eq. (4) resulting from the HSN instead of Eq. (3) to express the subcoolings including the $q^*_{cr,sat}$ resulting from the HSN for zero subcooling.

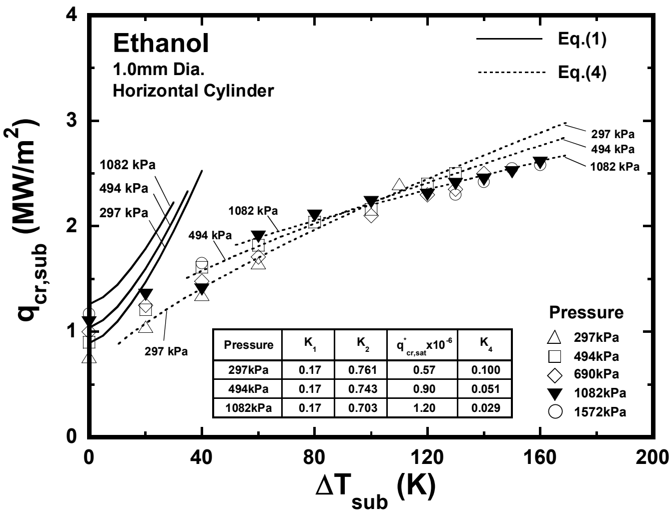

Fig. 6 Comparison of prediction representing $q_{cr,sub}$ related to subcooling at pressure as a parameter in ethanol using Eqs. (1) and (4).

$$q_{cr,sub} = q^*_{cr,sat}(1 + K_3 \Delta T_{sub}^{\ 0.73}) \tag{4}$$

$q^*_{cr,sat}$ value measured or extrapolated is used. The obtained K_1, K_2, $q^*_{cr,sat}$ and K_4 are shown in the table on the figure. The mechanism of heat transfer crisis at CHF and the properties, i.e., latent heat of vaporization, surface tension, density of saturation liquid etc. are greatly affected in CHF correlation. In the case of CHF data in a pool of ethanol which is highly wetting liquid, it has lower surface tension and its contact angle on cylinder surface is smaller than that of water, so that it may be easy for the liquid to flood cavities. Therefore, it can be seen on the figure that the CHFs from lower subcooling near saturated condition than that of water is due to HSN. As shown in the regime for the subcoolings higher than about 100 K with the corresponding CHF curves obtained from Eq. (4), the experimental data a little depending on the pressures are almost the same with the corresponding predicted values.

3.4 Trend of transient CHFs

Fukuda et al. [(18)] suggested the several empirical equations representing transient CHF values versus periods belonging to the first and second groups in a pool of water for wide range of subcoolings and pressures. The CHFs belonging to the first group caused by the heat generation rates with a long period under a saturated condition is expressed by the Eq. (5). The CHF belonging to the second group with a short period is expressed by the Eq. (6).

$$q_{cr} = q_{st,sub}\left(1 + 0.21\tau^{-0.5}\right) \quad , \quad \text{for 1st group} \tag{5}$$

$$q_{cr} = h_c\left(\Delta T_{in}(\tau) + \Delta T_{sub}\right) \quad , \quad \text{for 2nd group} \tag{6}$$

The symbol of h_c[(15)] is the heat transfer coefficient resulting from transient heat conduction. $\Delta T_{in}(\tau)$ is the initial boiling surface superheat due to the HSN in conduction regime, and measured for periods at every pressure. The CHF belonging to the first group with longer period occurs with a FDNB heat transfer process. At the second group with shorter periods, the direct transition to film boiling occurs with explosive-like boiling from non-boiling. It is considered that the direct boiling transition on the heater surface is due to the HSN as mentioned before.

3.4.1 Transient heat transfer up to critical heat flux

There exist two types of boiling incipience on the cylinder surface in a liquid due to an increasing heat input; one is that from originally unflooded active cavities entraining vapor and the other is that from another mechanism without contribution of the active cavities. The former is observed in water and the latter is in ethanol. The latter boiling mechanism was suggested by Sakurai et al. [7] to be due to the HSN from originally flooded cavities on the cylinder surface in the liquids. The heat transfer processes including the transition from the non-boiling regime to film boiling or to FDNB on a horizontal cylinder due to the exponentially increasing heat inputs at pressure was classified into three groups.

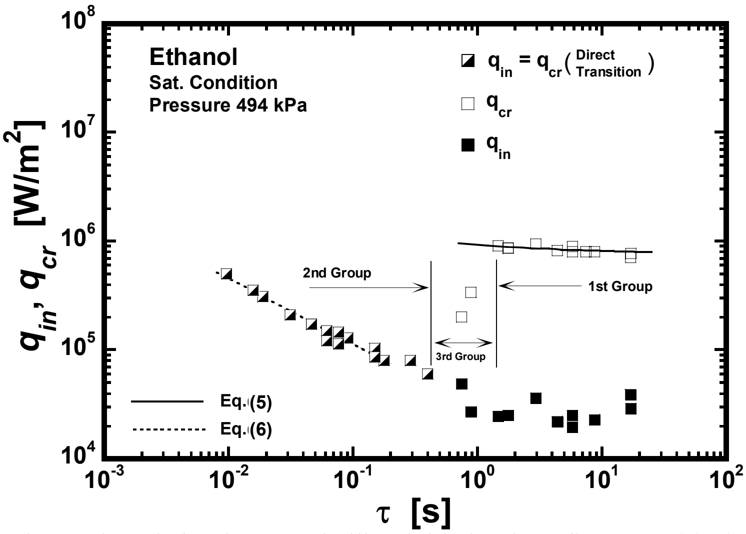

Fig. 7 The relation between boiling initiation heat flux q_{in}, critical heat flux q_{cr} and period τ in saturated ethanol at a pressure of 494 kPa.

Fig. 7 shows transient CHFs, q_{cr}, and initial boiling heat fluxes, q_{in}, versus periods, τ, ranging from 5 ms to 20 s in saturated ethanol at pressure of 494 kPa. The q_{cr} for the periods can be separated into three principal groups as shown in the figure; first group for the longer period shown with a solid line, second group for the shorter period shown with a dashed line and finally third group for the intermediate period between first and second group. It can be assumed that the q_{cr} values for the first group are on the extension of FDNB curve on q versus ΔT_{sat} as shown in Fig. 3. These values are considerably higher than the corresponding boiling initiation heat fluxes q_{in}. And the value of q_{cr} increases gradually with a decrease in the period from 20 s down to around 1.5 s. The q_{cr} of the second group ($\tau \leq 0.4$ s) is due to the direct transition from single-phase conduction regime to film boiling; the value q_{cr} is equal to q_{in}. It is considered that the direct boiling transition on the heater surface from non-boiling to film boiling is due to the HSN.

The relationship between q_{cr} and period τ for a pressure of 494 kPa in saturated water is shown in Fig. 8. The q_{cr} values belonging to first group are well expressed by Eq. (5) which represents the CHF due to the HI. The relationship is similar to that for the pressure of 494 kPa in ethanol shown in Fig. 7 except that the values of q_{cr} for periods shorter than 0.04 s are not equal to q_{in}. In the case of water, the second group does not appear at this pressure even during a shortest period test here. The reason is assumed that the boiling incipience on the cylinder surface in water causes an increasing heat input from originally unflooded active cavities entraining vapor bubbles. The cavity contributions to vapor

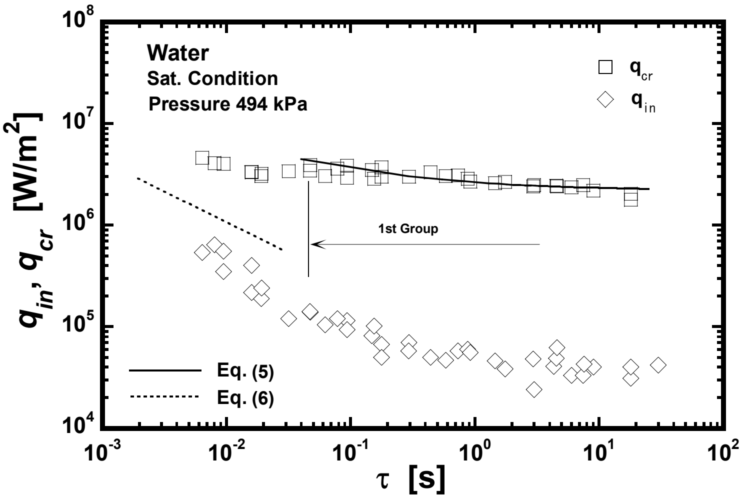

Fig. 8 The relation between boiling initiation heat flux q_{in}, critical heat flux q_{cr} and period τ in saturated water at pressure of 494 kPa.

forming are more than ethanol with flooded cavities, so that the heat flux slight increases with insufficient nucleate boiling. It can be found that there exist two types of boiling incipience on the cylinder surface in a liquid due to an increasing heat input. As a result, it should be noted that the mechanism in boiling incipience change with boiling liquids.

4. Conclusions

The generalized phenomena of transition to film boiling at steady and transient CHFs due to exponential heat generation rates with various periods were investigated. The major results lead to the conclusions as follows:

1. The transition processes were quite different from each other depending on experimental liquids. In the case of ethanol at atmospheric pressure, the transition superheats of initial boiling was much higher than that of water because the boiling initiation occurs from explosive-like HSN in flooded cavities not from active cavities in water.
2. The steady-state CHFs expected by the correlation based on HI existed in near saturated condition for the highly wetting liquids, and the heat transfer crisis at the CHFs belonging to high subcooling regime was assumed to occur resulting from the HSN in the fully-developed nucleation regime.
3. On the transient CHFs, there existed clearly the direct transition regime due to HSN in wetting liquids, but the direct transition was not appeared in the case of water. There were two types of boiling incipience from flooded cavities as well as from un-flooded active cavities depending on boiling liquids. The data measured gradually increased with an increase in subcooling.

Nomenclature

c_p	Specific heat at constant pressure, J/(kgK)
D	Cylinder diameter, m
h_{lv}	Latent heat of vaporization, J/kg
K_1	Coefficient in Eq. (3)
k	Thermal conductivity, W/(mK)
p	Pressure, Pa
p_c	Critical pressure, Pa
Q	Heat generation rate, W/m^3
Q_o	Initial heat generation rate, W/m^3
q_{cr}	Critical heat flux, W/m^2
$q_{cr,sat}$	q_{cr} for saturated condition, W/m^2
q_{st}	Steady-state critical heat flux, W/m^2
q_{in}	Boiling initiation heat flux, W/m^2
T_w	Heater surface temperature, K
$\Delta T_{sat} = (T_w - T_{sat})$	Surface superheat, K
$\Delta T_{sub} = (T_{sat} - T_B)$	Liquid subcooling, K
T_{sat}	Saturated temperature, K
T_B	Bulk liquid temperature, K
t	Time, s

Greek symbols

ρ	Density, kg/ m^3
σ	Surface tension, N/m
τ	Period, s

Subscript

l	Liquid
v	Vapor

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