



An Experimental Investigation of Transient Heat Transfer and Critical Heat Flux in Subcooled Pool Boiling

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Doctoral Dissertation

An Experimental Investigation of Transient Heat Transfer and Critical Heat Flux in Subcooled Pool Boiling

(サブクールプール沸騰における過渡熱伝達及び過渡限界熱流束に関する実験的研究)

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Abstract

The deep understanding of transient pool boiling critical heat flux (CHF) phenomena with treated surface and its correlation in water at saturated and subcooled conditions are becoming increasingly important for the database for the further enhancement of the design of liquid cooling technologies. Transient CHF using horizontal cylinders with different surfaces have been reported. However, there is a need to find the effect of surface wettability (contact angle) on transient CHF. This paper aims to study the steady and transient CHF due to exponentially increasing heat inputs, $Q=Q_0 \exp(t/\tau)$, using horizontal vertically oriented platinum ribbon in a pool of water with respect to pressure, subcooling, surface roughness and contact angle. The exponential period, τ , was varied from 5 ms to 10 s. We used three ribbon heaters with different surfaces, namely, commercial surface (CS), treated surface I (TS-I) polished by buff paper together with alumina, and treated surface II (TS-II) finished by emery paper.

Chapter (1) deals with the heat transfer and safety systems of nuclear reactor, problem statement of nuclear reactor, important high heat flux cooling for the safety for nuclear reactor and the structure of this study.

Chapter (2) concerns with literature review of boiling mechanism, nucleate boiling heat transfer and critical heat flux. Moreover, some the outcomes of some recent researches for nucleate boiling and critical heat flux are also mentioned.

Chapter (3) explains the method of surface making, the measured methods of surface roughness and contact angle. Moreover the experimental pool boiling apparatus, method and procedure which has been carried out throughout this research are explained in detail.

Chapter (4) mainly described the comparison of CHF for the kinds of heaters having different surface conditions and the effect of CHF on pressure and subcooling.

In this study, steady and transient CHF were reported. Steady state CHF was tested with the corresponding data obtained on commercial surface by Sakurai et al. Transient CHF were examined with previous corresponding correlations obtained on horizontal cylinder. Moreover, the CHF with different surface conditions were checked to the CHF correlations

with wettability (contact angle) to find their interconnection. The vapor behavior due to exponential increasing heat inputs on horizontal vertically oriented ribbon for TS-I was carried out.

Chapter (5) deals with the transient heat transfer and CHF for the condition of with and without pre-pressurization. The transient heat transfer were compared with the previous nucleate boiling heat transfer equation which includes the effect of solid-liquid combination.

Chapter (6) elucidates the heterogeneous spontaneous nucleation which was occurred at boiling initiation. The difference between typical boiling which come from active vapor filled cavity and the heterogeneous spontaneous nucleation are described. Moreover, the heat flux at boiling initiation are compared with the previous correlation with the effect of heterogeneous nucleation.

Chapter (7) mainly emphasized the general conclusions for the whole research. In the end of chapter (4), (5) and (6), I have explained the detailed conclusions as summary.

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Nomenclature

a	thermal diffusivity [m ² /s]
A_{k0}	energy of formation required for homogeneous nucleation
A_k	energy of formation required for the nucleation of a cavity
b	half-length of droplet base in Eq. (3.1) [m]
B	error of data acquisition system [V]
Bo	Bond number
c_p	specific heat at constant pressure [J/kgK]
C_{sf}	values of liquid-solid combination
C_1	coefficient in Taylor instability in Eq. (2.59)
D	diameter [m]
f	ratio of activation energy
f	frequency [1/s]
F_M	the force due to change in momentum [N]
$F_{S,1}$	surface tension force at the base of the bubble [N]
$F_{S,2}$	surface tension force at the top portion of the bubble [N]
F_G	pressure distribution [N]
H_b	bubble height [m]
g	acceleration of gravity [m/s ²]
G_b	Gibbs number
Gr_H^*	Grashot number
h	height of droplet in Eq. (3.1) [m]
H	characteristic length
H'	non-dimensionalization of characteristic length

h_c	conduction heat transfer coefficient [W/m ² K]
h_{lv}	latent heat of vaporization [J/kg]
h_n	natural convection heat transfer coefficient [W/m ² K]
h_m	combined heat transfer coefficient of natural convection and transient conduction [W/m ² K]
I	current flowing through standard resistance [A]
J	nucleation rate [1/m ² s ²]
Ja	Jakob number
J_0	proportionality
k	thermal conductivity [W/mK]
k	Boltzmann constant
K_1	coefficient in Eq.(2.41)
K_2	coefficient in Eq.(2.47)
K_3	coefficient in Eq.(4.5)
L	effective length of ribbon test heater [m]
N	number of molecular per unit volume [1/m ³]
N_a	nucleation site density [1/m ²]
N_c	number of cavities per unit surface area [1/m ²]
m	mass [kg]
Q	heat generation rate [W/m ³]
Q_0	initial heat generation rate [W/m ³]
P	system pressure [Pa]
P_m	maximum pre-pressure which is above threshold to change contact angle hysteresis inside the cavity [Pa]
$P_{m,min}$	amount of pre-pressure which is threshold to change contact angle hysteresis at

	cavity mouth [Pa]
ΔP	pressure difference inside vapor and liquid [Pa]
Pr	Prandtl number
q	heat flux [W/m^2]
q_{cr}	critical heat flux (CHF) [W/m^2]
$q_{cr,sat}$	CHF for saturated condition [W/m^2]
$q_{cr,sat}^*$	CHF resulting from HSN for saturated condition [W/m^2]
$q_{cr,sub}$	CHF for subcooled condition [W/m^2]
$q_{cst,sub}$	steady-state CHF for subcooled condition [W/m^2]
q_i	heat flux at boiling initiation [W/m^2]
q_I	heat flux at the interface [W/m^2]
R	gas constant [J/kgK]
R	resistance [Ω]
Ra	Rayleigh number
R_a	arithmetic mean roughness [μm]
R_q	root mean square roughness [μm]
R_1	resistance in bridge system [Ω]
R_2	resistance in bridge system [Ω]
R_3	resistance in bridge system [Ω]
r	radius [m]
r_k	critical nucleus radius [m]
S	precision error in data acquisition system [V]
$S_{\bar{x}}$	average precision error in data acquisition system [V]
T	liquid temperature [K]
T	temperature inside the test heater [K]

T_a	average temperature [K]
T_{bulk}	bulk temperature [K]
T_s	surface temperature of test heater [K]
T_{sat}	saturation temperature [K]
ΔT	temperature difference between surface and working fluid
ΔT_c	surface superheat at CHF [K]
ΔT_i	surface superheat at boiling initiation [K]
ΔT_{sat}	surface superheat = $(T_s - T_{sat})$ [K]
ΔT_{sub}	liquid subcooling = $(T_s - T_l)$ [K]
t	time [s]
u	uncertainty
V_I	voltage drop across standard resistance [V]
V_R	voltage drop across test heater [V]
V_T	unbalance voltage in a double bridge circuit [V]

Greek Symbol

δ	thickness of ribbon [m]
δ	vapor wave amplitude; vapor layer thickness [m]
δ	characteristic length of the geometry [m]
δ_t	thermal boundary thickness [m]
τ	exponential period [s]
σ	surface tension [N/m]
ρ	density [kg/m ³]
θ	contact angle [degree]
ϕ	orientation of test heater [degree]

μ	viscosity [Ns/m ²]
λ_c	critical wavelength corresponding to onset of instability [m]
λ_T	the wave length of the Taylor instability [m]
β	cavity angle (degree)
β	coefficient of volume expansion [1/K]
ν	kinematics viscosity of the fluid [m ² /s]

Subscripts

a	advancing (contact angle)
b	temperature condition at boiling initiation
b	bubble
B	bulk
cr	critical
h	heater
l	liquid
o	initial
r	receding (contact angle)
v	vapor

Chapter 1

Introduction

1.1 The heat transfer and safety systems of nuclear reactor

Nuclear reactor are associated with high power densities which require stringent heat transfer systems and needed higher level of operational safety. In nuclear reactor heat is generated by a concept of fission chain reaction of the isotopes called fuel elements or fissile elements. The generated heat is extracted and brought to a heat transfer system by a coolant which acts as not only the heat transfer medium but also a moderator to reduce the energy of fast fission energy to thermal equilibrium energy [1].

The basic conceptual diagram of pressurized water reactor (PWR) is shown in Fig.1.1 in which the heat from fuel elements are removed by primary cooling system using water and secondary cooling system by steam generating system. A nuclear reactor is usually equipped with chemical, thermal and mechanical safety systems. The control rods as shown in Fig.1.1 are examples of chemical and mechanical safety devices [2]. Recently, modifications of thermally safety systems have been implemented in pressurized water reactors by the installation of an alternative water supply source [3].

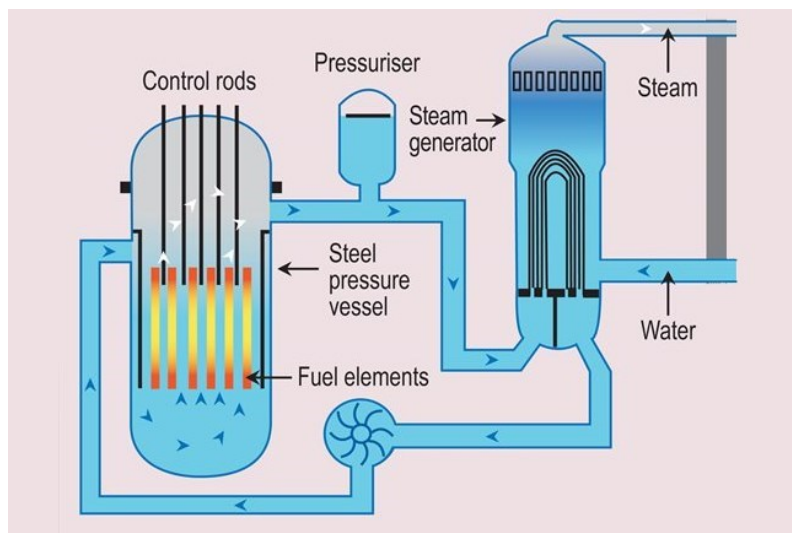


Fig. 1.1 The basic conceptual diagram of pressurized water reactor (PWR)

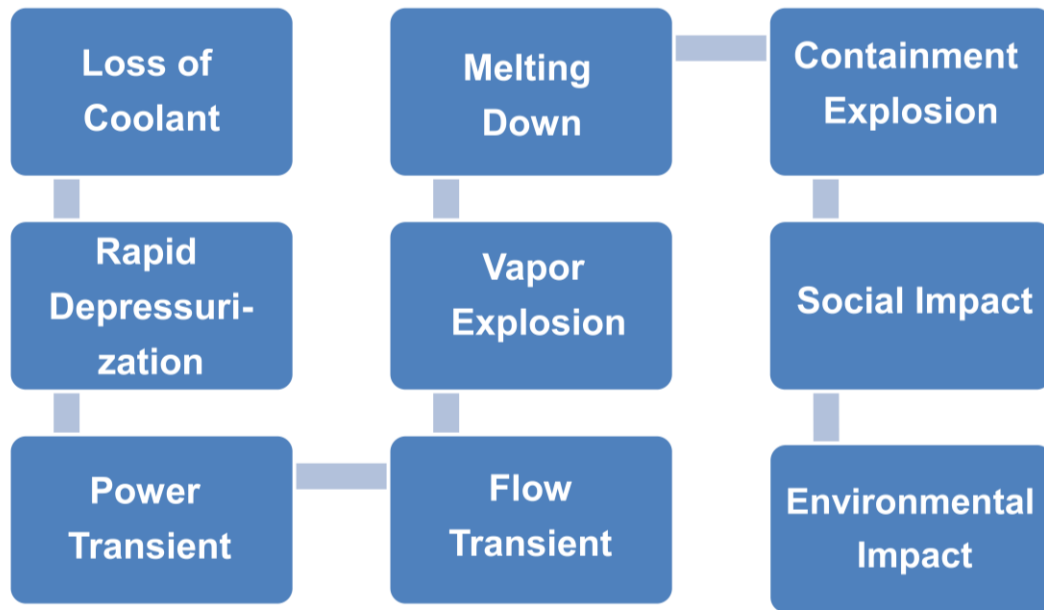


Fig. 1.2 Thermal hydraulic problems of nuclear reactors

Therefore, for the safety of nuclear reactors, the cooling of reactors are very important for the technical issue because the previous accidents of nuclear reactors are resulting from thermal hydraulic problems of reactors as shown in Fig. 1.2.

During the accidental condition of nuclear reactor, it is potential likely to be loss of coolant, rapid depressurization, power transient, flow transient and vapor explosion which leads to entire melting down of nuclear fuel, containment explosion, hydrogen explosion and so on. Severe accidents of nuclear reactors are also problems concerning with social and environmental for many years [4].

1.2 High heat flux cooling in nuclear reactor

1.2.1 Typical boiling curve

As cooling of nuclear reactor is motivated me as a research interest, the fundamental of boiling heat transfer and critical heat flux was carried out in this dissertation. Boiling has a complex phenomenon with natural convection, nucleate boiling, transition boiling and film boiling. Figure 1.3 shows typical boiling with natural convection from A to B, isolated nucleate boiling from B to C, fully developed nucleate boiling from C to D,

transition boiling from D to E and film boiling point from E to F. Boiling initiation or incipience occurs at point B. Critical heat flux is reached at point D.

Typical vapor behaviors corresponding to the respective boiling regimes are described in above the boiling curve in Fig. 1.3. Isolated bubbles can be seen at low heat flux and vapor column emerging from combining of vapor bubbles can be found in fully developed nucleate boiling at high heat flux region. In transition boiling, unstable nucleate and film boiling can be seen. Stable vapor film can be observed at film boiling [5].

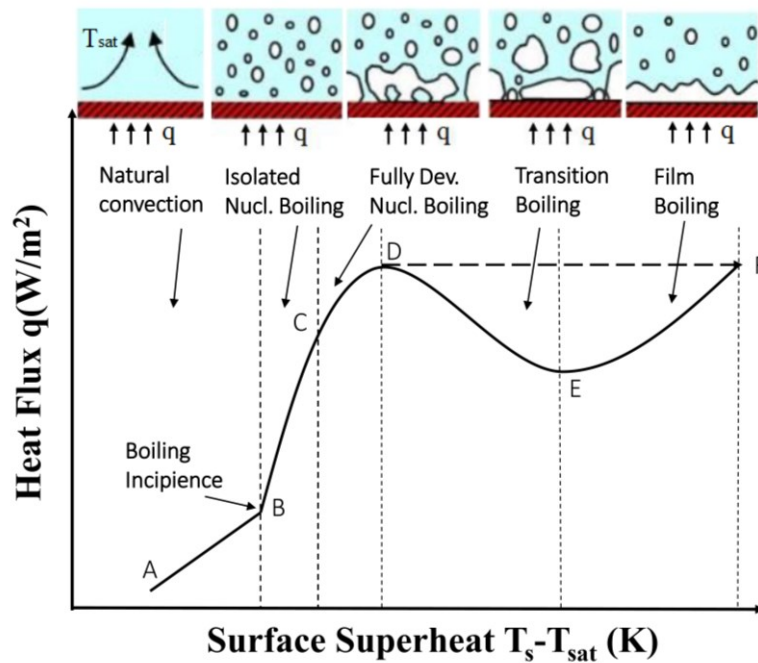


Fig. 1.3 Typical boiling curve and vapor behaviors for respective boiling regimes [5]

1.2.2 Characteristics of natural convection

In natural convection, when there is a temperature difference for a same fluid, the density also becomes change for that fluid. Then the fluid motion occurs by naturally due to buoyancy. Since the fluid velocity associated with natural convection is relatively low, the heat transfer coefficient encountered in natural convection is also low. Natural convection on a surface depends on the geometry of the surface as well as its orientation. It also depends on the variation of temperature on the surface and the thermophysical properties of the fluid.

The complexities of the fluid flow make it very difficult to obtain simple analytical relations for natural convection. Thus, most of the relationships in natural convection are based on experimental correlations with Rayleigh number (Ra), Grashof number (Gr) and Nusselt number (Nu).

The Rayleigh number [6] is defined as the product of the Grashof and Prandtl numbers,

$$Ra = Gr Pr = \frac{g\beta(T_s - T_\infty)\delta^3}{\nu^2} Pr \quad (1.1)$$

The Nusselt number in natural convection is in the following form:

$$Nu = \frac{h\delta}{k} = CR_a^n \quad (1.2)$$

where the constants C and n depend on the geometry of the surface and the flow.

1.2.3 Characteristics of nucleate boiling heat transfer

Nucleate boiling heat transfer is one of the most efficient modes of heat transfer for a wide range of applications such as chemical plants, refineries, nuclear power plants, and food industry. The superiority of nucleate boiling heat transfer is obtained through the latent heat of evaporation in the departing vapor bubbles and via sensible heat in the superheated liquid rising from the surface [7].

During nucleate boiling, the heat flux q increases with an increase of the temperature difference, ΔT , between the surface and the working fluid until a critical heat flux (CHF) is reached. Higher heat transfer coefficients depend on the bubble characteristics in terms of size, frequency, and departure rate.

There have been many attempts to enhance nucleate boiling heat transfer researches on the effects of liquid properties, surface conditions, heating, pressure and subcooling. It was occurred that the heat transfer coefficient and surface superheat are depending not only the liquid properties but also heated surface conditions. Heated surface conditions also have complicated effects on boiling heat transfer. Surface condition are determined by the values of surface roughness and contact angle. Recently, many researchers reported boiling heat transfer and CHF on the effects of surface roughness and contact angle. Some of them have controlled the surface roughness and contact angle with nano porous coating

or oxidation or chemical means. It is assumed that those methods of surface modification are inconsistent in time. Some researchers have made structured surfaces. Most of the researches reported generally that the values of surface roughness and contact angle leads to surface superheat and heat transfer coefficient. Those results come from the trapped vapor in cavities of the heating surface and are corresponding to the critical equilibrium radius according to the vapor trapping mechanism.

1.2.3.1 Heterogeneous spontaneous nucleation (HSN)

However, the method of pre-pressurization to the heating surface in the boiling vessel can make not only the contact angle hysteresis but also liquid filled cavity instead of vapor filled cavity. In this condition, the boiling comes from heterogeneous spontaneous nucleation mechanism. The existing of heterogeneous spontaneous nucleation (HSN) was investigated by means of experimentally and photographically. The heterogeneous spontaneous nucleation commences from surface at high temperature which is also called HSN temperature. The occurrence of explosive-like-vapor behavior was observed at HSN temperature. It was assumed that the surface condition such as surface roughness and contact angle have shaped heterogeneous spontaneous nucleation.

1.2.4 Characteristics of critical heat flux (CHF)

There is a limitation of the heat flux in a boiling system. It is called critical heat flux (CHF) where temperature of heating surface increases suddenly with heat transfer crisis. The deep understanding of CHF is important for the safety of industrial applications.

Moreover, mechanism responsible for critical heat flux (CHF) is still research interest to understand in detail. Mechanism of critical heat flux is mainly suggested based on the hydrodynamic instability. Hydrodynamic instability model is a reliable model for a certain condition. However, in this model, it is lack of consideration of near field effect such as heater surface condition. Many attempts on critical heat flux have been carried out to find the effect of surface conditions as non-hydrodynamic approach. Most of them mainly emphasized on the steady state condition of critical heat flux though the insight of mechanism which mainly influents the critical heat flux is quite complicated.

1.2.4.1 Critical heat flux due to heterogeneous spontaneous nucleation

Transient boiling heat transfer and CHF is also very important for the safety of nuclear reactor. Reactivity initiated accident (RIA) is one the design parameter in the evaluation of light water reactors which can increase to the temperature of fuel and cladding exponentially [8]. In this context, transient power excursion can occur to fuel and cladding. Recently, the researchers in our laboratories suggested the CHF mechanism due to HSN which differs from hydrodynamic instability mechanism. They have also widely reported the transient boiling heat transfer and CHF for wide ranges of pressure, subcooling and heat generation rate. However, transient boiling heat transfer and CHF on the effect of wettability (contact angle) is needed to examine.

1.2.5 Aim of this research

In this study, we performed the experimental boiling heat transfer and CHF due to HSN on the effects of surface roughness as well as contact angle because they are interconnecting. Surface roughness and contact angle is controlled by surface finishing method by using buff paper together with Al_2O_3 liquid and emery paper. The three kinds of platinum ribbon were prepared having different surface roughness and contact angle such as commercial surface (CS), treated surface-I (TS-I) and treated surface-II (TS-II). The following investigations shown in Fig. 1.4 are carried out.

- (1) To investigate surface roughness and wettability (contact angle) on boiling heat transfer and CHF
- (2) Orientation effect on CHF
- (3) Effect of pressure
- (4) Effect of subcooling
- (5) Pre-pressurization effect on boiling initiation or onset of nucleation and CHF
- (6) Mechanism of transient CHF
- (7) Heterogeneous spontaneous nucleation which influence to CHF

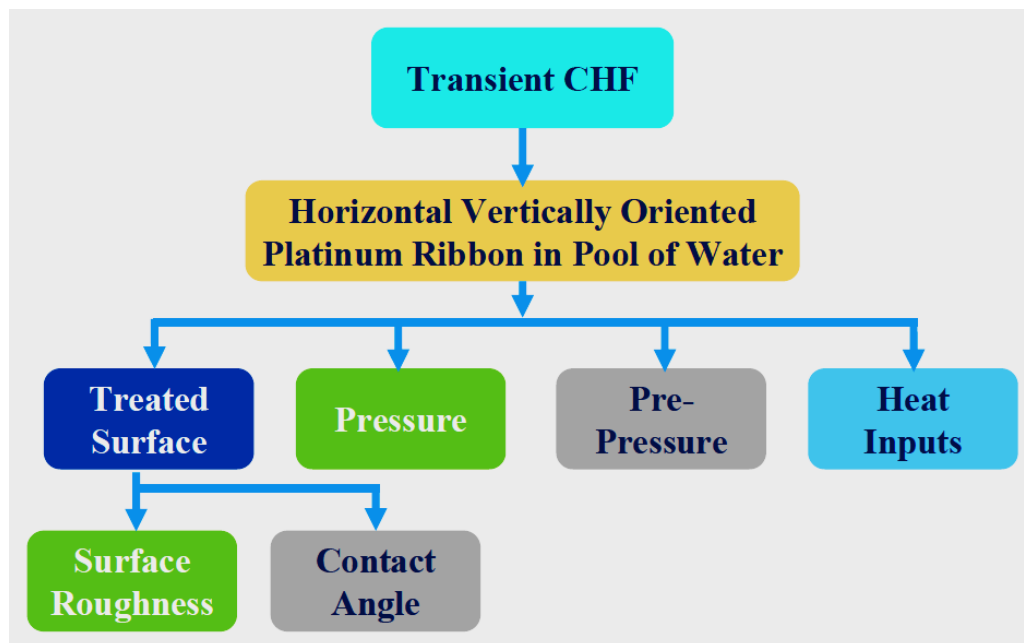


Fig. 1.4 Structure of the transient CHF study

Chapter 2

Literature Review

2.1 Theory discussion of the origin of boiling

2.1.1 Bubble formation from active cavities

Boiling takes place irregularities of the heating surface. There exist vapor trapped cavities in the heating surface. Boiling commences from those vapor trapped cavities are called boiling initiation due to active cavities.

2.1.2 Nucleation from flooded cavities or heterogeneous nucleation

However, as there is no cavity in smooth surface, vapor cannot trapped in it. Moreover, in some cases, cavities are filled with liquid instead of vapor and they become flooded cavities. In those condition, the occurrence of boiling initiation is interesting. Generally it is called boiling initiation due to heterogeneous nucleation. The formation of heterogeneous nucleation is a quite complicated phenomenon.

According to the Corty and Foust [9], the formation of heterogeneous nucleation is assumed according to the two mechanisms: the oscillations and pressure surges may create increased supersaturation in neighboring cavities, allowing nucleation to take place there; the second proposed mechanism postulates that a bubble, originating in a cavity of submicroscopic size, will grow far beyond it and may cover many other cavities before breaking loose. Thus, vapor may be trapped in many cavities and they may become active centers.

2.1.3 Surface superheat requirement of boiling initiation due to active cavity

To start boiling from vapor trapped cavity or active cavity, mechanical and thermal equilibrium of vapor exist in the cavity and liquid. Griff and Wallis [10] suggested the following relation by mechanical and thermodynamic equilibrium,

$$\Delta P = \frac{2\sigma}{r} \quad (2.1)$$

where, ΔP is the pressure difference of vapor and liquid, $(P_v - P_l)$, σ is surface tension at liquid-vapor interface and r is radius of cavity mouth. Assuming contact angle at liquid vapor interface as $\theta = 90^\circ$ and the curvature of vapor at cavity mouth is the smallest radius, r , which is the same to cavity radius, r_c .

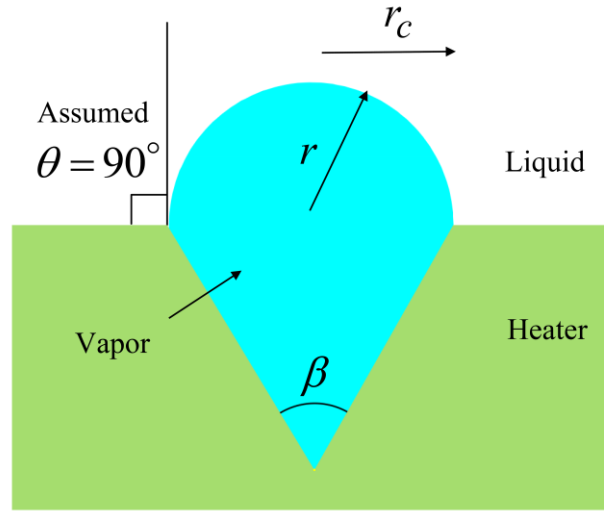


Fig.2.1 Boiling initiation from cavity mouth to superheated liquid which are in the condition of mechanical and thermodynamic equilibrium (Griff and Wallis)

However, many researchers reported origin of boiling or boiling initiation on the effects of contact angle, surface roughness. Corty and Foust examined the effects of the interface-variables due to surface roughness and contact angle at the heat transfer surface on nucleate boiling. Contact angle is important for nucleation primarily and cavity mouth determine surface superheat needed. Corty and Foust [9] suggested the following relation assuming the boiling originates from the inside of the cavity.

$$\Delta P = \frac{2\sigma[\cos(\beta/2 - \theta)]}{r} \quad (2.2)$$

In Eq. (2.2), boiling commences when $r=s$ which are demonstrated in Fig. 2.2.

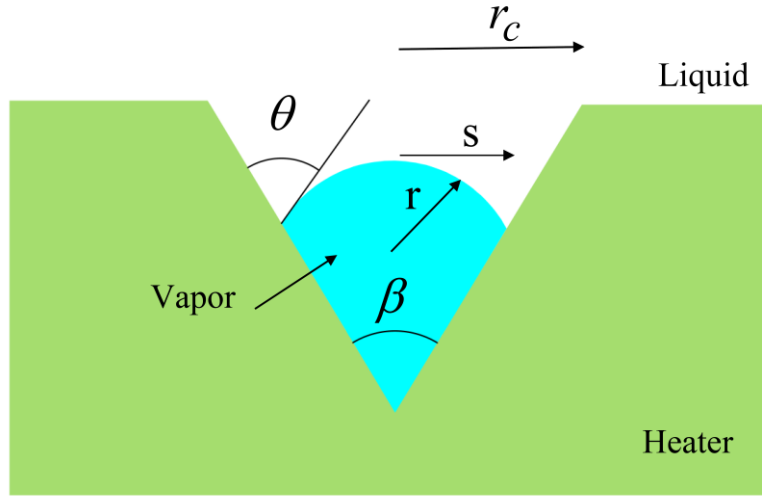


Fig.2.2 Boiling initiation occurs inside cavity to superheated liquid

In equilibrium condition of a vapor and liquid, temperature inside vapor and liquid at the plane of interface must be the same temperature. As the vapor pressure is higher than liquid pressure, the temperature of liquid which corresponds to saturated vapor temperature becomes superheated temperature. By taking the relation of superheated liquid temperature and excess pressure of the vapor bubble, the Clausius-Clapeyron correlated as follow,

$$\Delta P = \frac{(T_s - T_{sat})h_{lv}\rho_v}{T_{sat}} \quad (2.3)$$

when substitute the ΔP in Eq. (2.1) is substitute to Eq. (2.3), the surface superheat at boiling initiation is obtained as follow,

$$(T_s - T_{sat}) = \frac{2\sigma T_{sat}}{rh_{lv}\rho_v} \quad (2.4)$$

2.1.4 Surface superheat of heterogeneous nucleation

2.1.4.1 Thermal boundary layer thickness model

Hsu [11] studied heterogeneous nucleation in a cavity have a mouth radius of r_c on superheated liquid in pool boiling. He took into consideration of liquid temperature gradient near the heated surface. To grow into a bubble from vapor, Hsu postulated that the liquid surrounding the bubble must be superheated liquid temperature corresponds to saturated vapor temperature in vapor. Moreover, the thickness of superheated liquid layer is associated with the height of bubble and the radius of bubble. In turn, the bubble height and the radius of bubble are associated with the radius of cavity, r_c . Hsu proposed the surface superheat needed to boiling initiation from the above relation as follow,

$$\delta_t = \frac{12.8\sigma T_{sat}(T_s - T_l)}{\rho_v h_{lv}(\Delta T_{sat})^2} \quad (2.5)$$

where, δ_t is thermal boundary layer thickness estimated as k_l/h . The heat transfer coefficient is taken as $h = q/(T_s - T_l)$. In the superheated liquid layer, the heat transfer according to the conduction governs and the Eq. (2.5) is substituted to heat conduction equation gives the required heat flux at boiling initiation or onset of nucleation

$$q_i = \frac{h_{lv}\rho_v(T_s - T_{sat})^2}{12.8\sigma\rho_v T_{sat}} \quad (2.6)$$

2.1.4.2 Heterogeneous nucleation on wettability

Recently, Quan, et al. [12] developed the radius of cavity by modification of Hsu's model of heterogeneous nucleation on a heated surface by taking into consideration of wettability from the view point of changes in Gibbs free energy. They obtained radius of cavity, r_c , which in turn has the relation of surface superheat as follow,

$$r_c = \frac{2R\rho_v\sigma T_{sat} [(5 - 3\cos\theta)T_s + (3 - \cos\theta)T_{sat}]}{\rho_l h_{lv} (5 - 3\cos\theta)(T_s - T_{sat})} \quad (2.7)$$

2.1.4.3 Heterogeneous nucleation on smooth surface

Heterogeneous nucleate boiling was also observed on ultra-smooth surfaces with root mean square (RMS) roughness of $0.03 - 0.365 \mu\text{m}$ for brass, unpolished stainless steel, and electropolished stainless steel in pentane and butane at steady boiling condition according to the Bon, et al. [13].

2.1.4.4 Heterogeneous nucleation on pre-pressurization

However, Faw, et al. [14] have found that temporary pre-pressurization which can make contact angle hysteresis and variation of mechanical equilibrium at liquid-vapor interface leading to changes in thermodynamic equilibrium is one of the factor affecting boiling initiation. Contact angle hysteresis is the difference between solid-liquid-vapor interface which advances over unwetted surface in a cavity, θ_a , and recedes over a previously wetted surface, θ_r .

Alternatively, highly subcooling can change thermodynamic equilibrium resulting variation in mechanical equilibrium and it can lead to contact angle hysteresis.

Suppose $\beta/2 \geq \theta_a - \pi/2$, where, $\beta/2$ is half cavity angle. When contact angle of a liquid advances over previous unwetted cavity, the cavity becomes flooded cavity. In this condition, boiling initiation from flooded cavity is concerning with free energy fluctuation [15-16]. It will be explained in next article.

However, there will be a situation in which $\beta/2 \leq \theta_a - \pi/2$ because surface roughness is difficult to be consistence for whole heating surface.

Boiling initiation due to heterogeneous nucleation induced by contact angle hysteresis due to subcooling and pre-pressurization is explained here.

(i) Contact angle hysteresis at solid-liquid-vapor interface due to subcooling

In a subcooled condition at a pressure of a liquid, P_o , the temperature of liquid-vapor interface which is corresponding to vapor pressure, P_{v_a} , will be less than the superheated

temperature of a liquid at that pressure and then vapor pressure, P_{v_a} , can be less than the liquid pressure, P_o . The greater the liquid pressure, the greater the advancing contact angle as shown in Fig. 2.3. In this condition, the radius of curve of vapor, r , is the same to radius meniscus, r_o . Then radius meniscus is equivalent to

$$r_o = \frac{2\sigma_a}{(P_o - P_{v_a})} \quad (2.8)$$

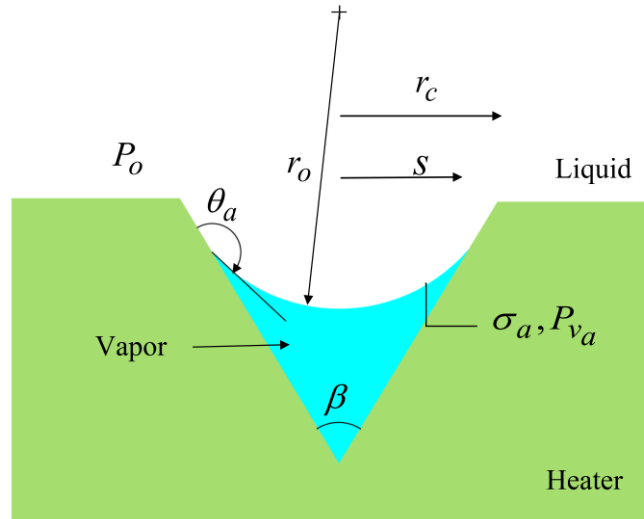


Fig.2.3 Liquid-vapor interface at initial condition due to subcooling

The radius of meniscus line of contact, s , as shown in Fig. 2.3 is

$$s = r_o \cos(\pi - \theta_a + \beta/2) \quad (2.9)$$

Substitute Eq. (2.8) in Eq. (2.9),

$$s = \frac{2\sigma_a \cos(\pi - \theta_a + \beta/2)}{(P_o - P_{v_a})} \quad (2.10)$$

Then, mechanical equilibrium at boiling initiation as shown in Fig. 2.4 is

$$P_{v_b} - P_o = \frac{2\sigma_b \cos(\theta_r - \beta/2)}{s} \quad (2.11)$$

Substitute Eq.(2.10) in Eq. (2.11),

$$P_{vb} - P_o = \frac{\sigma_b \cos(\theta_r - \beta/2)}{\sigma_a \cos(\pi - \theta_a + \beta/2)} (P_o - P_{va}) \quad (2.12)$$

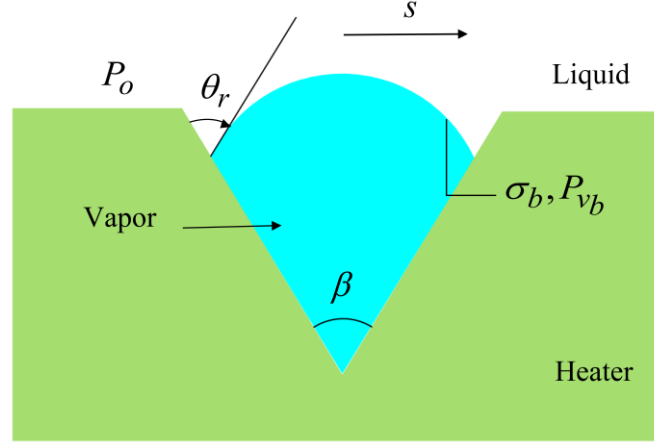


Fig. 2.4 Liquid-vapor interface at boiling initiation due to subcooling

(ii) Contact angle hysteresis at solid-liquid-vapor interface due to pre-pressurization

Suppose mechanical and thermodynamic equilibrium of the solid-liquid-vapor interface at cavity mouth at a pressure of P_o , and corresponding surface tension, σ_o , and

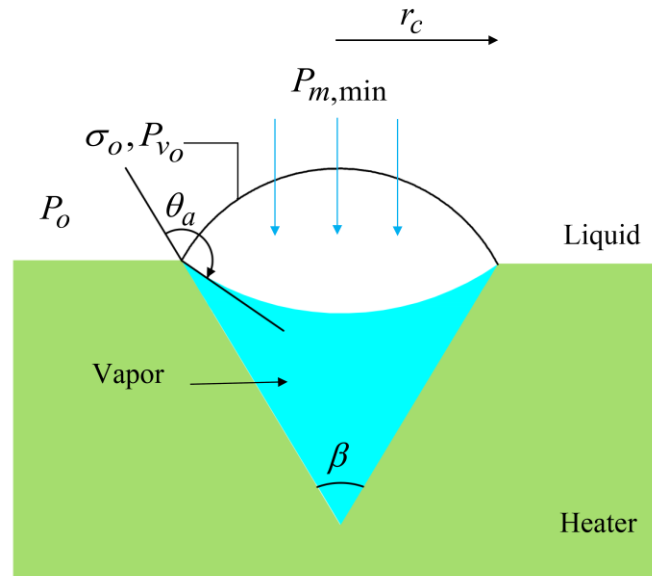


Fig. 2.5 Contact hysteresis at liquid-vapor interface at cavity mouth due to pre-pressurization ($P_{m,min}$)

vapor pressure, P_{v_o} , as shown in Fig. 2.5. If some amount of pre-pressure which is threshold to change contact angle hysteresis at cavity mouth, $P_{m,\min}$, is exerted to liquid-vapor interface, it changes to be concave shape and contact angle become advancing contact angle, θ_a , as indicated in Fig. 2.5. Then mechanical equilibrium at cavity mouth is

$$P_{m,\min} - P_{v_o} = \frac{2\sigma_o \cos(\pi - \theta_a + \beta/2)}{r_c} \quad (2.13)$$

If maximum pre-pressure, P_m , which is above the threshold is exerted to liquid-vapor interface as shown in Fig. 2.6, the mechanical equilibrium is

$$P_m - P_{v_o} = \frac{2\sigma_o \cos(\pi - \theta_a + \beta/2)}{s} \quad (2.14)$$

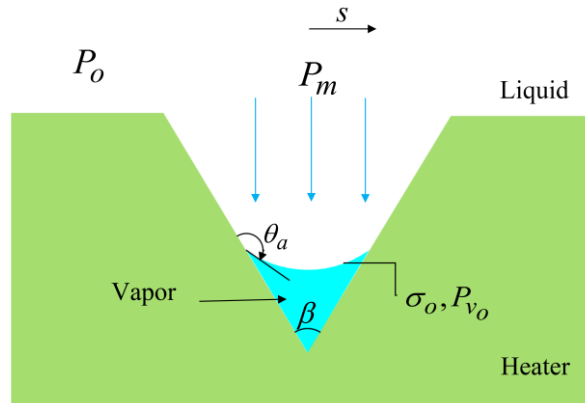


Fig. 2.6 Liquid-vapor interface due to pre-pressurization (P_m)

Then, mechanical equilibrium at boiling initiation as shown in Fig. 2.7 is

$$P_{v_b} - P_o = \frac{\sigma_b \cos(\theta_r - \beta/2)}{\sigma_o \cos(\pi - \theta_a + \beta/2)} (P_m - P_{v_o}) \quad (2.15)$$

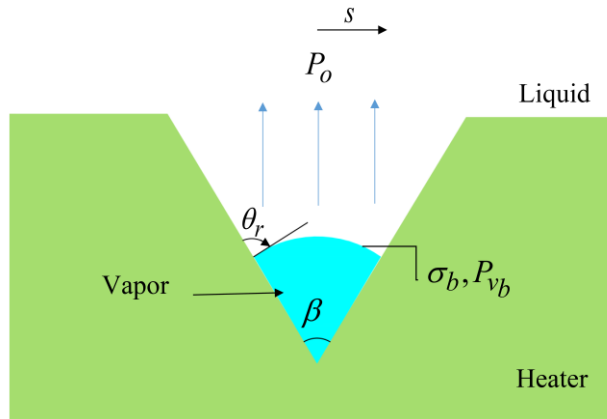


Fig. 2.7 Liquid-vapor interface at boiling initiation due to pre-pressurization (P_m)

2.1.4.5 Heterogeneous spontaneous nucleation on wettability (contact angle) and cavity angle

Kottowski [15] reported the heterogeneous nucleation in a liquid is primarily a process of free energy fluctuation of void formation or homogeneous nucleation. He proposed that heterogeneous nucleation occurs due to free energy change of homogeneous nucleation. He suggested the free energy change depends on contact angle and cavity angle. He also proposed free energy required for heterogeneous nucleation by modification of correlation of homogeneous nucleation. As liquid nitrogen is used as working fluid, the effect of trapped vapor was not taken into account into consideration.

The illustration of contact angle, cavity angle and the cavity without trapped vapor is shown in Fig. 2.8.

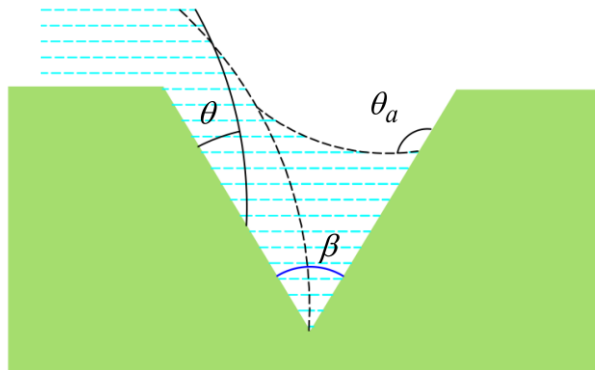


Fig. 2.8 The illustration of contact angle, cavity angle and the cavity without trapped vapor

Sakurai and Fukuda [16] were the first ones stated the existing of heterogeneous spontaneous nucleation (HSN). They examined formation of HSN and temperature required for HSN. The experiments were performed by means of pre-pressurization and power transient which is exponentially increasing heat input. By pre-pressurization, they have suggested that the surface having active cavities with vapor pockets change to flooded cavities with liquid as shown in Fig. 2.8. Therefore, there is no active nuclei in cavities. At a certain high superheat, it was occurred that the bubbles come out spontaneously from the heating surface with explosive-like-boiling. They contributed the correlation of pressure-temperature relation for the heterogeneous spontaneous nucleation.

The maximum free energy required for homogeneous nucleation [15] is as follow,

$$A_{k0} = \frac{4}{3} \sigma \pi r_k^2 \quad (2.16)$$

Again, when Eq. (2.1) is substitute to Eq. (2.16),

$$A_{k0} = \frac{16\pi\sigma^3}{3(\Delta P)^2} \quad (2.17)$$

where, A_{k0} is the maximum free energy required for the formation of homogeneous nucleation, and r_k is the critical nucleation radius by Kottowski.

The ratio of activation energy [15] is defined as free energy required for heterogeneous nucleation to free energy required for homogeneous nucleation as follow,

$$f = \frac{1}{4} \left[2 - 3 \sin \left(\theta - \frac{\beta}{2} \right) + \sin^3 \left(\theta - \frac{\beta}{2} \right) \right] \quad (2.18)$$

The heterogeneous nucleation is the free energy change from homogeneous nucleation due to variation of critical nucleation radius, contact angle, θ , and cavity angle, β , on a heated surface as follow,

$$A_k = \frac{A_{k0}}{4} \left[2 - 3 \sin \left(\theta - \frac{\beta}{2} \right) + \sin^3 \left(\theta - \frac{\beta}{2} \right) \right] \quad (2.19)$$

$$A_k = \frac{1}{3} \sigma \pi r_k^2 \left[2 - 3 \sin \left(\theta - \frac{\beta}{2} \right) + \sin^3 \left(\theta - \frac{\beta}{2} \right) \right] \quad (2.20)$$

where, A_k is the maximum free energy required for the formation of heterogeneous nucleation.

In terms of a Gibbs number [17-18], free energy required for homogeneous nucleation relates to the typical kinetic energy of the molecules, namely, kT , (k is Boltzmann's constant) as follow,

$$G_b = A_{k0} / kT \quad (2.21)$$

The above relation is considered to the heterogeneous nucleation,

$$G_b = A_{k0} f / kT \quad (2.22)$$

Moreover, nucleation rate has the relation with Gibbs number as follow,

$$J = J_0 e^{-G_b} \quad (2.23)$$

In above equation, J_0 is proportionality. For homogeneous nucleation, Blander and Katz [19] gives as follow,

$$J_0 = N \left(\frac{2\sigma}{\pi m} \right)^{1/2} \quad (2.24)$$

For heterogeneous nucleation, Sakurai [16] gives J_0 as follow,

$$J_0 = N^{2/3} S \left(\frac{2\sigma}{\pi m B f} \right)^{1/2} \quad (2.25)$$

where, $B = 2/3$, and

$$S = \frac{1}{2} \left[1 - \sin \left(\theta - \frac{\beta}{2} \right) \right] \quad (2.26)$$

When the equations (2.17) and (2.22) are substituted to Eq. (2.23), the pressure-temperature relation for HSN equation is obtained.

$$\Delta P = \left[\frac{-16\pi\sigma^3 f}{3kT \ln(J_0/J)} \right] \quad (2.27)$$

In above equations, contact angle, θ , and cavity angle, β , are difficult to estimate, Sakurai [16] gives the following empirical correlations, Eqs. (2.28-2.31), for the predictions of HSN in Eq.(2.27).

$$S = \exp \left[-21.6 \left(1 - 0.52e^{-60Z} \right) Z^{0.1} \left(\frac{T_{cr} - T}{T_{cr}} \right) \right] \quad (2.28)$$

$$f = \frac{1}{4} \left[2 - 3(1 - 2S) + (1 - 2S)^3 \right] \quad (2.29)$$

$$Z = \frac{\sigma_B T_{cr}}{(T_{cr} - T_B)} \quad (2.30)$$

$$\sigma = \left[\frac{\sigma_B T_{cr}}{(T_{cr} - T)} \right] \left[\frac{(T_{cr} - T)}{T_{cr}} \right]^{1.28} \quad (2.31)$$

Figure 2.9 shows the theoretical demonstration of HSN correlation based on the Eq. (2.27). The demonstration represents the result of pre-pressurization condition and without consideration of the effect of cavity angle. It can be seen that the surface superheat at boiling initiation, $\Delta T_i = T_s - T_{sat}$, is depending on the contact angle and less depending

to the nucleation rate, J . The ΔT_i increases up to 200 K with the decreasing of the contact angle. The ΔT_i is too high at lower contact angle. For this reason, it is considered there may be two influenced factors such as not only the contact angle but also the cavity angle. However, the cavity angle is practically difficult to measure. Moreover, the value of contact angle hysteresis vigorously is debated for a long time.

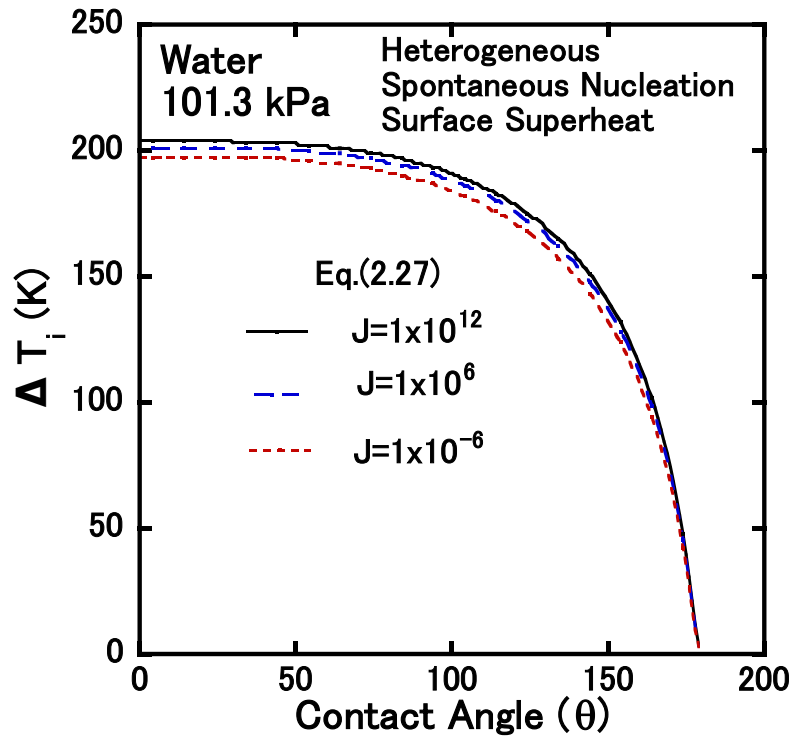


Fig. 2.9 The theoretical demonstration of HSN correlation (Eq. 2.27)

Figure 2.10 shows the demonstration of the lower limit of HSN temperature versus pressure in saturated water using Eqs. (2.27-2.31). Nucleation rate, J , of 1×10^6 was considered for calculation, however, it has less influence on the relation. Saturated temperature is indicated in the figure for the reference. As the increase of saturated temperature corresponds to pressure, the lower limit of HSN temperature also increase with the increase of pressure.

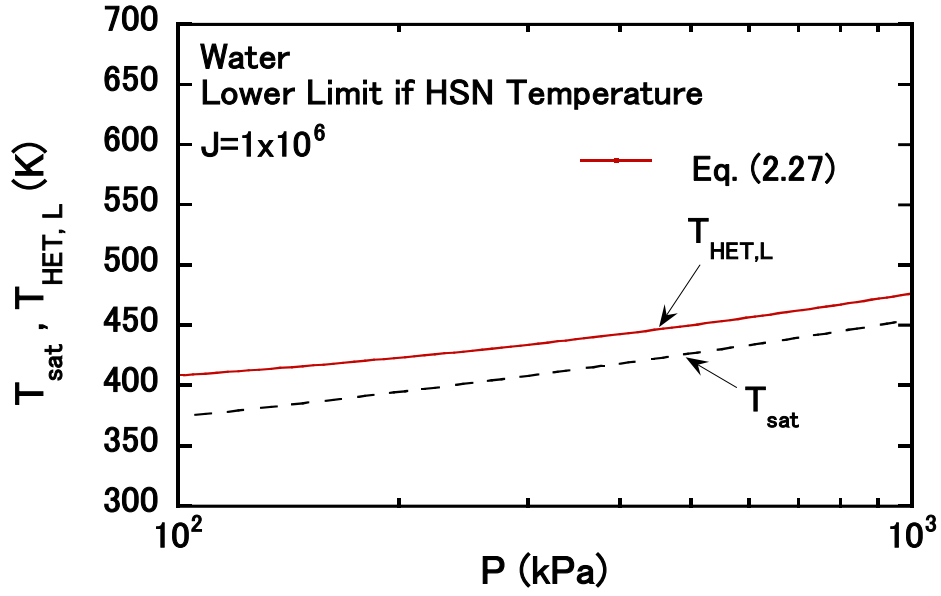


Fig. 2.10 The relation between lower limit of HSN, $T_{HET,L}$ and pressure

2.2 Nucleate boiling heat transfer model

Many researchers such as Kutateladze, Stephan and Abdelsalam, Cooper, Forster and Zuber, and Rohsenow proposed the various nucleate boiling heat transfer model. Some of them suggested the following nucleate boiling correlations.

2.2.1 Nucleate boiling heat transfer on hydrodynamic theory

Kutateladze [20] proposed nucleate boiling heat transfer on hydrodynamic theory as follow,

$$\frac{h}{k_l} \sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}} = 7.0 \times 10^{-4} \text{Pr}_l^{0.35} \left[\frac{q}{\rho_v h_{lv} \nu_l} \sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}} \right]^{0.7} \left[\frac{P}{\sigma} \sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}} \right]^{0.7} \quad (2.32)$$

2.2.2 Nucleate boiling heat transfer on nucleation site density and thermal properties

Nakayama [21] suggested nucleate boiling heat transfer on nucleation site density and thermal properties. He suggested the following equation for water,

$$q = \left(\frac{\pi D_b^3}{6} \right) N_a f_b h_{lv} \rho_v + \left(\frac{\Delta T}{1.95} \right)^{1/3} N_a^{1/3} \quad (2.33)$$

where,

$$N_a = N_c (1 - \cos \theta) \Delta T \quad (2.34)$$

$$f_b D_b = 0.59 \left[\frac{\sigma g (\rho_l - \rho_v)}{\rho_l^2} \right]^{0.25} \quad (2.35)$$

$$Bo^{1/2} = 0.04 Ja \quad (2.36)$$

$$Ja = \frac{(T_w - T_{sat}) C_{pl} \rho_l}{\rho_v h_{lv}} \quad (2.37)$$

$$D_b = \left[\frac{\sigma Bo}{g (\rho_l - \rho_v)} \right]^{1/2} \quad (2.38)$$

2.2.3 Nucleate boiling heat transfer on surface-fluid combination and thermal properties

Rohsenow [22] proposed nucleate boiling heat transfer taking into consideration of surface-fluid combination and thermal properties,

$$q = \mu_l h_{lv} \left[\frac{g (\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{c_{pl} \Delta T_{sat}}{C_{sf} h_{lv} Pr_l^n} \right)^3 \quad (2.39)$$

2.2.4 Nucleate boiling heat transfer on transient conduction heat transfer

Su, et al. [23] correlated transient conduction heat transfer on the effects of thermal effectivity of liquid and heater, critical nucleation radius, and heat generation period,

$$q_{tr,cond} = \left(\sqrt{\frac{k_l \rho_l c_{pl}}{\tau}} \right) \left[T_{sat} \left(P_{atm} + \frac{2\sigma}{r_c} \right) - T_l \right] \exp \left(\frac{r_c}{\sqrt{k_h \rho_h c_{ph} \tau}} \right) \quad (2.40)$$

2.3 Nucleate pool boiling heat transfer on surface roughness and contact angle

2.3.1 Surface modification techniques

So far, many researchers have carried out various techniques dealing with factors influencing nucleate boiling heat transfer. Some of the techniques are chemical, mechanical, and surface modification techniques. Moreover, they have attempted to enhance boiling heat transfer. However, in this study, the effect of surface condition on boiling heat transfer is mainly investigated.

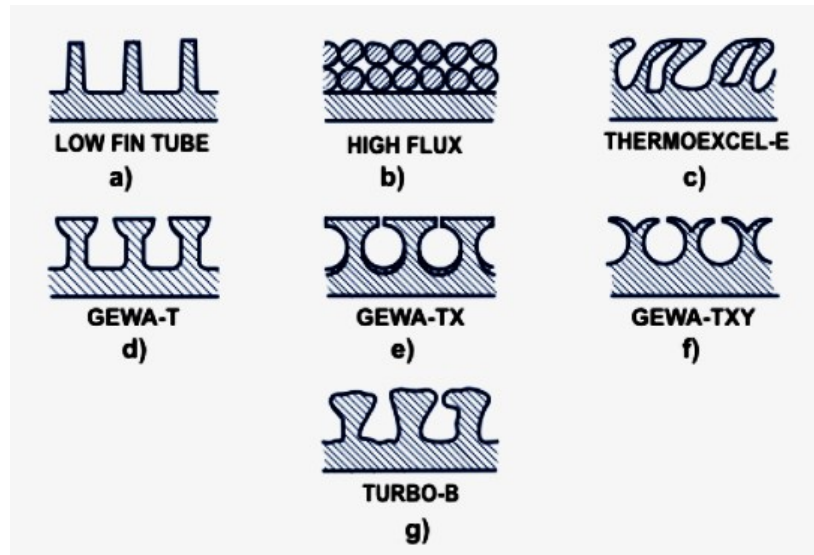


Fig. 2.11 Examples of commercial structured boiling surfaces

Surface modification includes change of (i) geometrical structure; (ii) microscale roughness; and (iii) coatings of various types in terms of surface energy and hydrophobicity [7]. Figure 2.6 shows examples of commercial structured boiling surfaces.

2.3.2 Nucleate boiling heat transfer on bare copper, carbon nano tube and sandblasted copper surface

Recently, nucleate boiling heat transfer on heating surface characteristics on wettability and microstructures or roughness are research interest and it was assumed that they will play important role in boiling heat transfer [24].

Dharmendra, et al. [25] conducted the pool boiling heat transfer experiments on bare copper, sandblasted copper and vertically aligned carbon nano tube (CNT) coated copper substrates in water at atmospheric pressure. The surface roughnesses and contact angles of the bare copper, sandblasted copper and CNT coated copper substrates are $0.25\ \mu\text{m}$, $1.95\ \mu\text{m}$ and $2.34\ \mu\text{m}$, and 70° , 54.9° and 133.5° , respectively. CNT coated surface was

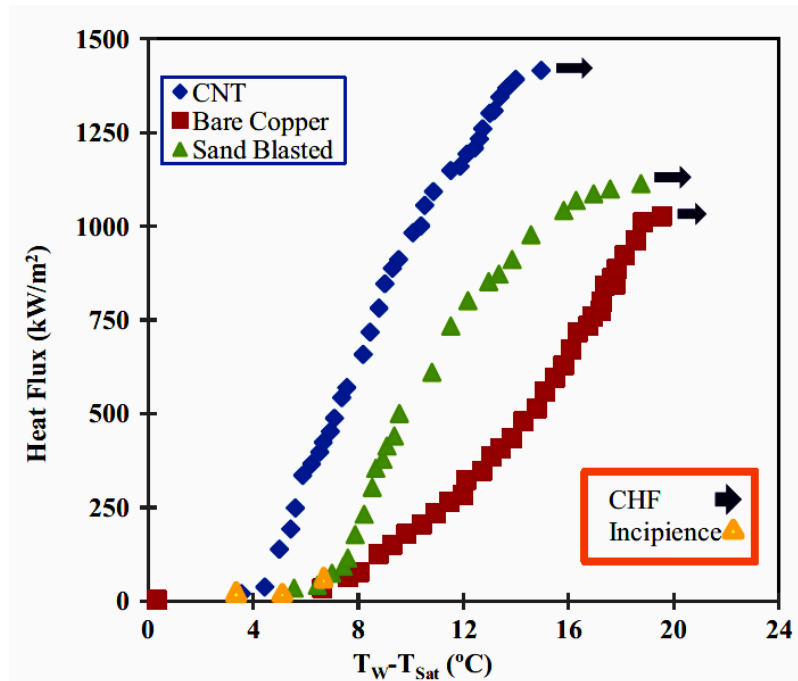


Fig. 2.12 Nucleate boiling heat transfer for CNT coated copper, bare copper and sand blasted copper surfaces

observed to be effective in increasing the nucleate boiling and CHF enhancement of 38 % relative to bare copper. Figure 2.12 shows the heat flux vs. surface superheat for this test. The enhancement of nucleate boiling and CHF depend on increasing values of surface roughness. However, they are not depend on contact angle. It was noted that sandblasted copper has increased surface roughness and decreased contact angle values compared to the bare copper.

2.3.3 Nucleate boiling heat transfer on microporous coatings

Kim, et al. [26] carried out an experimental study to maximize the boiling heat transfer with the effect of microporous coatings. The surface roughness was controlled by making the various test heaters of microporous coating by using ABM (aluminum particles, brushable ceramic epoxy, and methyl ethyl ketone) and thermally conductive microporous coating (TCMC). All test heaters were $1\text{ cm} \times 1\text{ cm}$ in dimension in the upward-facing orientation. They were performed in R-123 refrigerants and water.

The nucleate boiling heat transfer coefficients and critical heat flux (CHF) enhance on

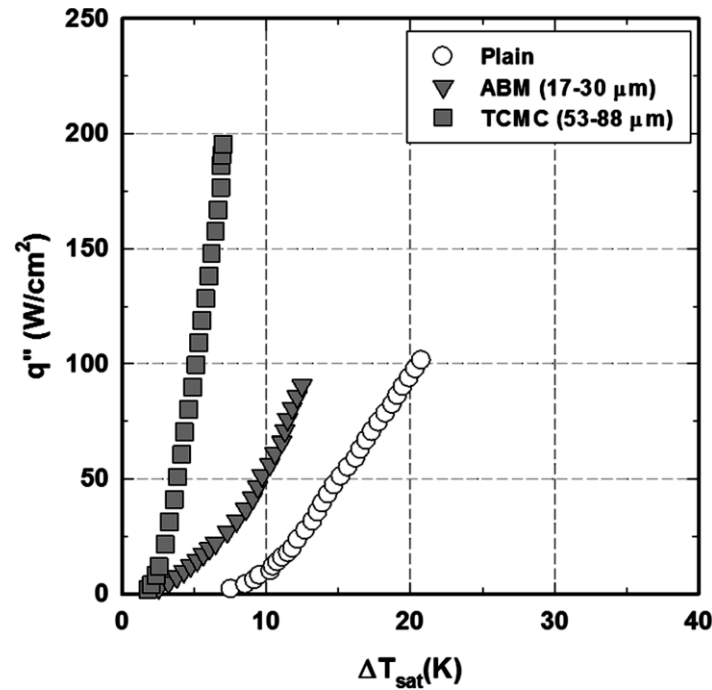


Fig.2.13 Nucleate boiling heat transfer for plain, the conductive microporous coating (TCMC), and ABM coating in saturated water at atmospheric pressure

the heaters with the ABM coatings in R-123 depending on the increases of surface roughness. On the other hand, the boiling performance on ABM coatings did not improve and did not depend on surface roughness in water.

However, for water, the enhancement of boiling performance which depend on surface roughness was found on TCMC coatings. The heat transfer coefficient increased up to ~5.6 times, and doubling the CHF on TCMC coating in water compared to plain surface.

Moreover, it was occurred that the surface roughness alone did not influence the boiling performance for the different coatings such as ABM and TCMC according to the Fig. 2.13 in which the best performance of ABM has surface roughness of 17-35 μm and TCMC has 53-88 μm , respectively.

2.3.4 Nucleate boiling heat transfer on nano porous structures

Zhang, et al. [27] studied the enhanced heat transfer performance in nucleate boiling by the effect of surface wettability. They determined the surface wettability by static contact angle. They utilized two methods to control the surface wettability.

One is the use of the Alumina sponge-like nano-porous structure (ASNPS). The ASNPS has characteristics of an enlarged surface area, increasing number of the active nucleation site density, and improved the vapor–liquid menisci. It is assumed to be representative of the reentrant pore.

Another method of changing the surface wettability is using with a hydrophobic self-assembled monolayer (SAM) coating. It can also improve the number of active nucleation site density. The surface made by the combination of SAM and the previous ASNPS is also called SASNPS.

The contact angles of ASNPS and SASNPS are 50.0° and 150.0° , respectively, which are shown in Fig.2.14 (a) and (b). The heat transfer performance of plain, ASNPS and SASNPS are shown in Fig. 2.15. According to this experimental result, large contact angle on the SASNPS has enhanced nucleate boiling heat transfer performance. Moreover, Zhang et al., suggested the effect of thickness of those surfaces and modified previous Nakayama's the heat flux correlation.

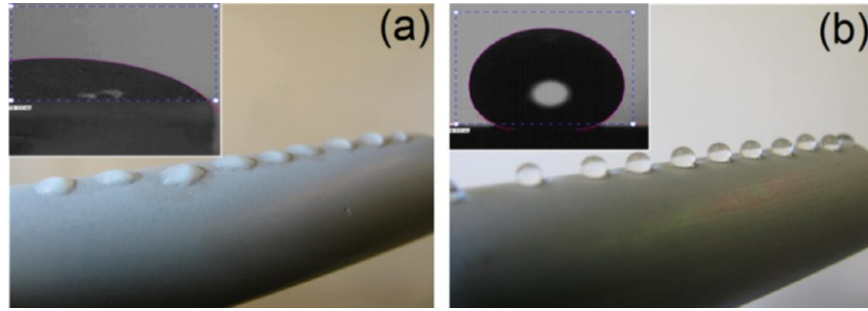


Fig. 2.14 Water contact angle: (a) ASNPS with 50.0° and (b) SASNPS with 150.0°

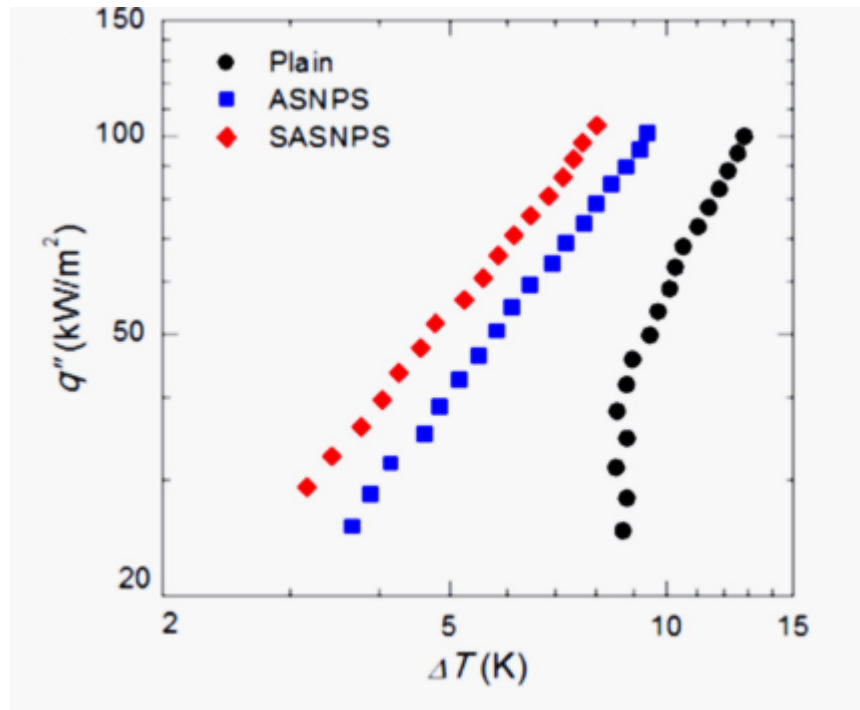


Fig. 2.15 Nucleate boiling heat transfer for Plain, ASNPS and SASNPS

2.3.5 Nucleate boiling heat transfer on SiO₂ layer (hydrophilic) and combined Teflon material and SiO₂ (hydrophobic)

Jo, et al. [24] reported effect of heterogeneous wetting surfaces on nucleate boiling heat transfer in water. They prepared the hydrophilic (54.0°) surface made of SiO₂ layer and hydrophobic (123.0°) surface fabricated by Teflon material to SiO₂ layer using MEMS

techniques. The average surface roughness, R_a , for SiO_2 and hydrophobic surfaces are $1.75 \mu\text{m}$ and $4.38 \mu\text{m}$, respectively. In the low heat flux regime, hydrophobic surface proves better nucleate boiling heat transfer than hydrophilic surface as shown in Fig. 2.16. However, in high heat flux, SiO_2 contributes better heat transfer performance. The contradictions of heat transfer on wettability and surface roughness were occurred on hydrophilic, SiO_2 and hydrophobic surfaces.

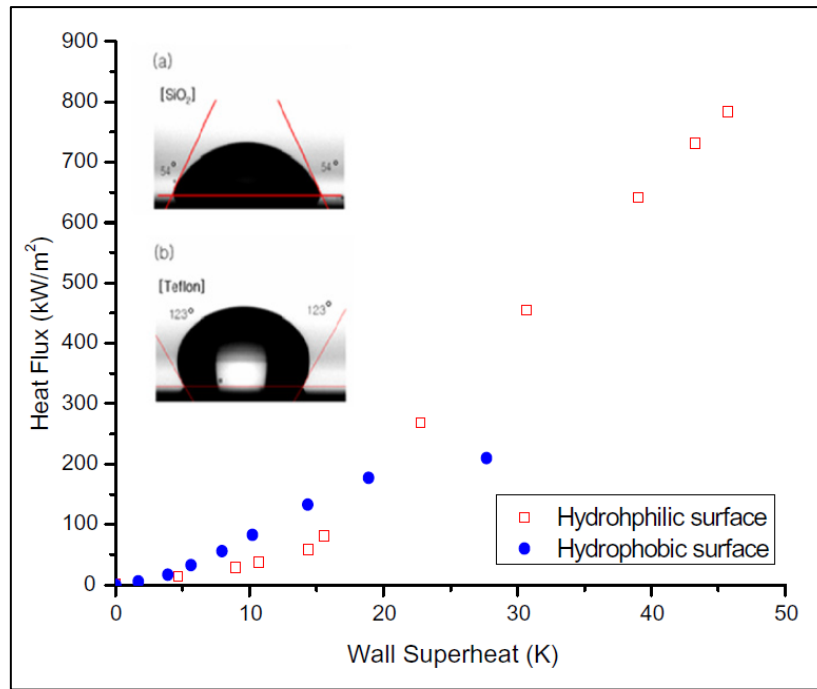


Fig. 2.16 Nucleate boiling heat transfer on (a) SiO_2 surface as a hydrophilic surface and (b) Teflon patterned surface as hydrophobic surface

2.3.6 Nucleate boiling heat transfer on pressure and power transient

Sakurai [16] conducted transient heat transfer experiment on 1.2 mm horizontal cylinder in water at saturated condition under atmospheric pressure. The horizontal cylinder was heated by exponentially increasing heat inputs with various period from 10 s – 10.9 ms. Moreover, the experiments were carried out by the conditions of without pre-pressure (case 1) and with pre-pressure up to 5 MPa (case 2). The reason of pre-pressure is to remove vapor trapped cavities and become wetted or flooded cavities.

Figure 2.17 shows the heat transfer processes for the case of without pre-pressure (case 1) and pre-pressure up to 5 MPa (case 2). For the case of without pre-pressure (case 1) and heat input rate of 10 s, the heat transfer process as shown in solid line increases from natural convection to CHF through fully developed nucleate regime. On the other hand, for the case of pre-pressure up to 5 MPa (case 2) and for various heat input rate, all the heat transfer processes as shown in broken lines go to film boiling directly. Sakurai suggested this phenomenon as heterogeneous spontaneous nucleation (HSN).

Fukuda and coworkers [28-35] investigated multi models of heterogeneous spontaneous nucleation.

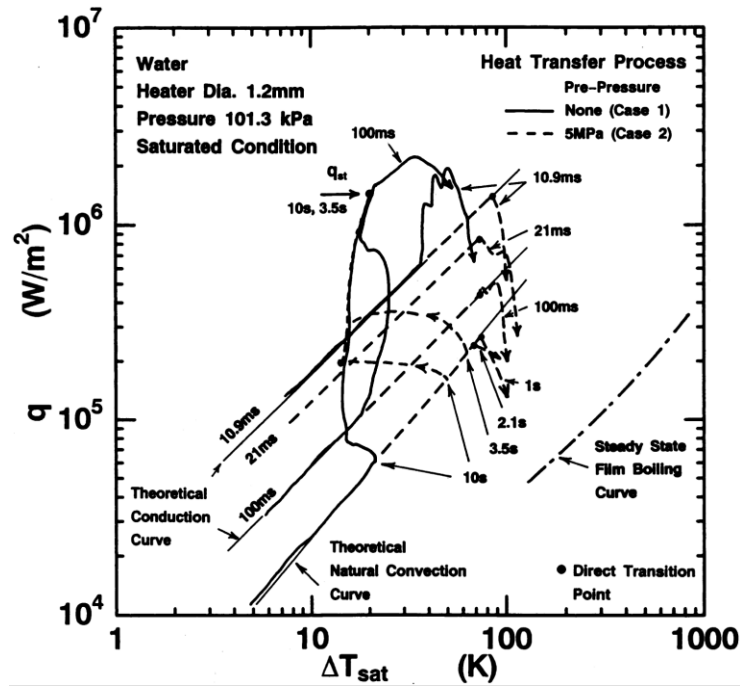


Fig. 2.17 Heat transfer processes for period for the condition of with and without pre-pressure

The vapor behavior of HSN on 1.2 mm horizontal cylinder in water due to exponential heat inputs of 982 ms at saturated condition under atmospheric pressure is shown in Fig. 2.18. The HSN vapor cover the surface of cylinder completely at time taken of 15 ms and CHF reached instantaneously. The similar vapor behavior is observed at the work of Avksentyuk and Mamontova and, Avksentyuk, et al. [36-37].

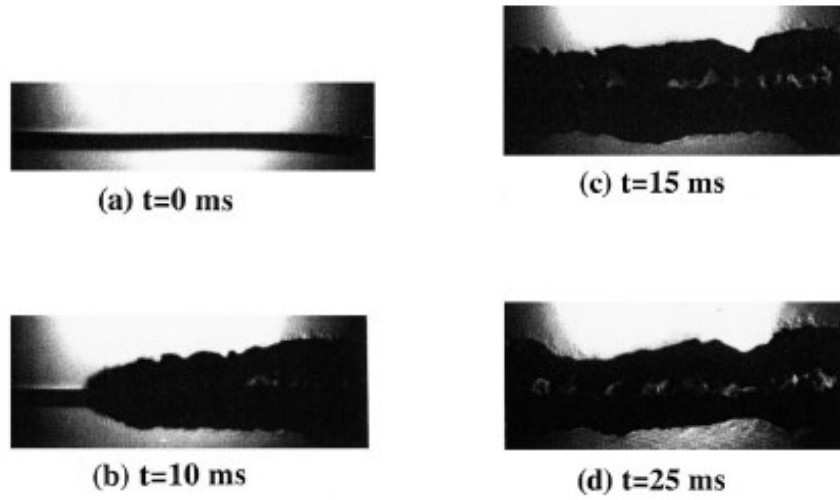


Fig. 2.18 The vapor behavior of HSN on 1.2 mm horizontal cylinder in water due to exponential heat inputs of 982 ms at saturated condition under atmospheric pressure

2.3.7 Nucleate boiling heat transfer on wettability by different liquid

Park, et al. [33] performed heat transfer process on different wettability using water and ethanol as shown in Fig. 2.19. At the same experimental condition, direct transition to film boiling due to HSN was occurred only for the ethanol.

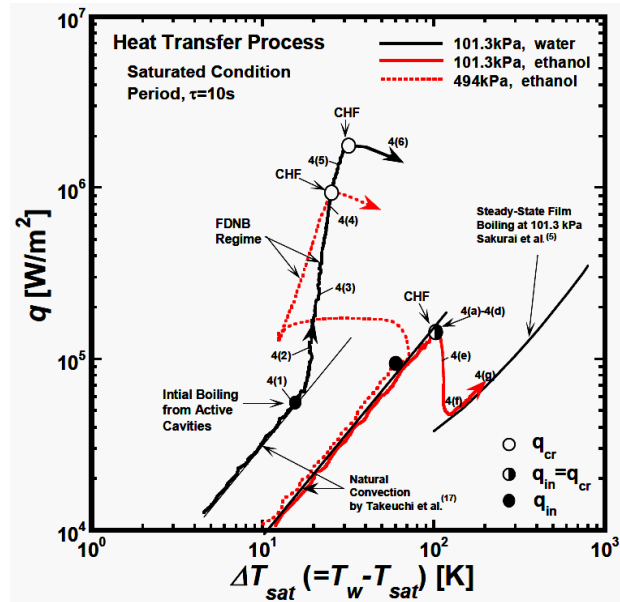


Fig. 2.19 Typical heat transfer process for period of 10 s for different wettability in saturated water and ethanol at atmospheric pressure

2.4 Theory discussion of the CHF mechanism

2.4.1 Hydrodynamic aspect of CHF

CHF has usually been predicted based on the existing database and correlations. There are some well-known correlations and accomplishments as the following. Many researchers correlated CHF based on hydrodynamic instability model.

Kutateladze [38-39] correlated CHF according to the hydrodynamic instability model.

$$q_{cr,sat} = K_1 h_{lv} \rho_v \left[\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4} \quad (2.41)$$

Firstly, Kutateladze proposed the constant of K_1 to be 0.16. Later he modified it to be 0.14. Zuber [40] also derived the same Eq. (2.41) from his experiments and the constant of K_1 was obtained as 0.1309.

Lienhard and Dhir [41] modified the Eq. (2.41) to include the geometrical effect of heating surface. For the small horizontal vertical oriented ribbon, they proposed the following equation.

$$\frac{q_{cr,Lienhard}}{q_{cr,sat,Z}} = \frac{1.18}{\sqrt[4]{H'}} \quad (2.42)$$

where, $q_{cr,sat,Z}$ is CHF for saturated condition by Zuber's correlation which is the same with Eq. (2.41). H' is characteristic length with the relation of $H' = H \sqrt{g(\rho_l - \rho_v)/\sigma}$.

Surface orientation is an important factor that can greatly affect the CHF. Vishnev, El-Genk and Guo, Chang and You and, Howard and Mudawar examined the effects of orientation on pool boiling CHF. They also correlated the CHF equations associated with surface orientation.

Genk and Guo [42] separately correlated CHF equations with surface orientation for water, liquid nitrogen and liquid helium. The correlation with water is as follows,

$$q_{cr,sat} = C_{CHF,water}(\theta) h_{lv} \rho_v \left[\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4} \quad (2.43)$$

$$\text{where, } C_{CHF,water}(\theta) = 0.034 + 0.0037(180 - \theta)^{0.656} \quad (2.44)$$

Howard and Mudawar [43] studied the CHF trigger mechanism by dividing the three regions of surface orientations: upward-facing ($0 - 60^\circ$), near-vertical ($60 - 165^\circ$) and downward-facing ($> 165^\circ$). The upward-facing surface achieves the maximum CHF due to removing vapor vertically off the heater surface by buoyancy forces. Conversely, downward-facing heater has the least CHF due to difficult bubble detachment. In near-vertical region, a wavy liquid-vapor interface which sweeps along the heater surface is occurred. The vapor bubble behavior of various orientation is shown in Fig. 2.20.

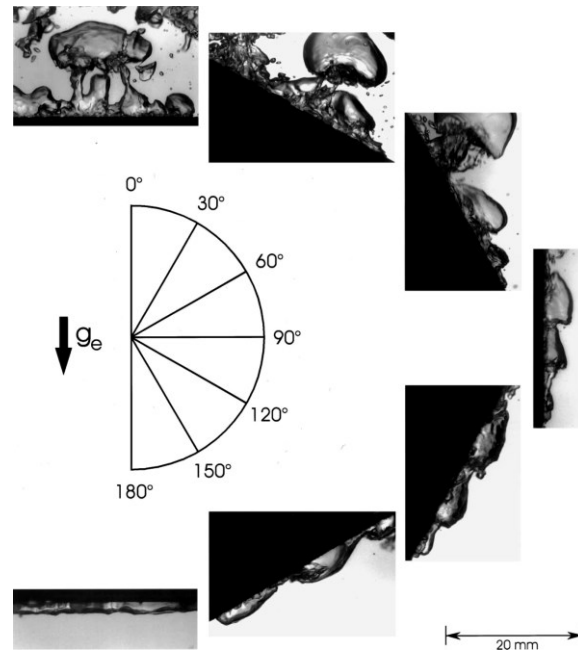


Fig. 2.20 The vapor bubble behavior of various orientation

Upward-facing surfaces have been extensively examined by many researchers and downward-facing surfaces have carried out by a few researchers. The near-vertical region is interesting because the near-vertical CHF model includes classical two-dimensional interfacial instability theory and a criterion for separation of the wavy interface from the surface at CHF. The CHF correlation for saturated water for the near vertical regime is given as follow,

$$q_{cr,sat} = \frac{1}{4} h_{lv} \rho_v \left(1 + \frac{c_{pl} \Delta T_{sub}}{h_{lv}} \right) \left[(2\sqrt{2}\pi) \frac{\sigma \delta}{\rho_v \lambda_c^2} \right]^{1/2} \quad (2.45)$$

Sakurai and Fukuda [16] derived CHF correlation based on the Kutateladze's equation. They have carried out experiments using various heaters such as horizontal cylinders having different dimension, and horizontal platinum ribbon for wide ranges of pressure and subcooling in water pool boiling. The heat is supplied by the methods of exponentially increasing heat inputs.

Figure 2.21 shows the typical CHF data on horizontal vertically oriented ribbon with the corresponding correlations. The solid lines are according to the correlation based on the hydrodynamic instability theory and the broken lines are according to the heterogeneous spontaneous nucleation (HSN).

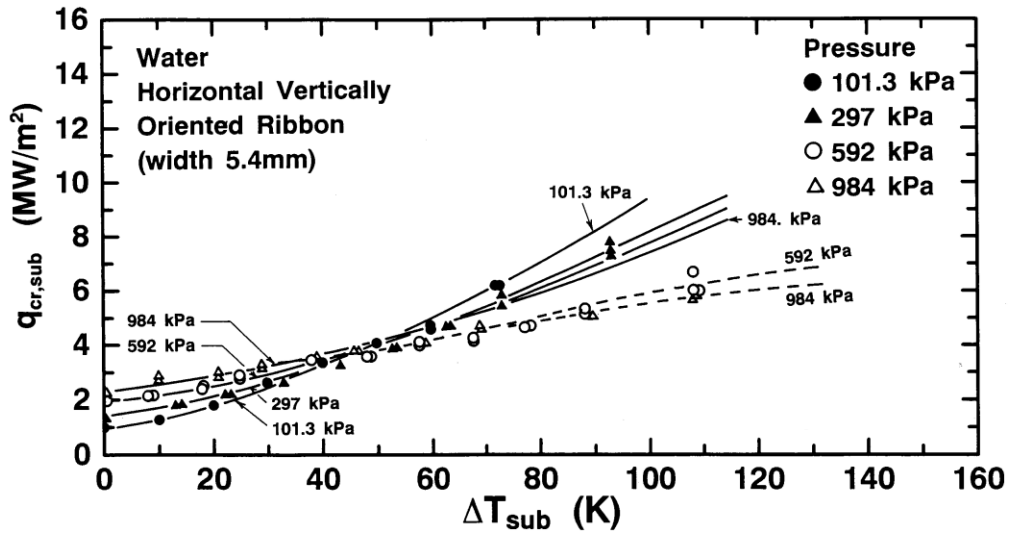


Fig. 2.21 The typical CHF data on horizontal vertically oriented ribbon with the corresponding correlations

Among various correlations, I would like to points of those for horizontal vertically oriented ribbon. The following correlations are given for commercially available horizontal vertically oriented platinum heater under saturated and subcooled condition, respectively, based on the hydrodynamic instability theory which are also described in the figure.

$$q_{cr,sat} = 0.12 h_{lv} \rho_v \left[\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4} \quad (2.46)$$

$$q_{cr,sub} = q_{cr,sat} \left[1 + K_2 \left(\frac{\rho_l}{\rho_v} \right)^{0.69} \left(\frac{c_{pl} \Delta T_{sub}}{h_{lv}} \right)^{1.5} \right] \quad (2.47)$$

where, The values of K_1 and K_2 were suggested as 0.12 and 0.679 for horizontal vertically oriented ribbon [16].

2.4.2 Non-hydrodynamic aspect of CHF

Although CHF was well defined as hydrodynamic phenomenon, a number of investigated the important role of surface conditions on CHF. Some of the CHF tests which were emphasized on surface condition for non-hydrodynamic characteristics are indicated in Table 2.1

Tachibana, et al. [44] investigated the non-hydrodynamic aspects of CHF. They used more than 400 piece of flat plates as test sections made of various metals and alloys such as stainless steel, nickel, aluminum, copper, molybdenum, phosphor bronze, lead, indium and constantan. They were tested in horizontal and vertical orientation in saturated water under atmospheric pressure. The trend of CHF's seems to be possible a general correlation between the CHF and the heat capacity of heating surface area. The trend also becomes asymptotic value with increasing the above parameter which shows partial proof of hydrodynamic theories of CHF. However, aluminum and precipitated stainless steel shows higher value of CHF than general trend. They concluded that interfacial property such as a good affinity with water can increase CHF.

Golobic and Bergles [45] examined the effects of heater-side factors on the saturated pool boiling CHF. The CHF experiments have been conducted on noninsulated horizontal vertically oriented ribbon heaters with different materials in FC-72 fluid and the effects of ribbon thermal properties and thickness were determined. They proposed a practical criterion for sizing ribbon heaters without significant conductance/capacitance effects on CHF.

Table 2.1 Pool boiling experimental conditions and distinguished surface characteristics tested for non-hydrodynamic CHF characteristics

Authors	Heaters	Working Fluid and Condition	Exponential Period	Distinguished Surface Characteristic	Results
Tachibana	Ribbon made of various material	Water, 101.3 kPa	Steady	Aluminum and precipitated stainless steel	CHF increase
Golobič and Ferjančič	Ribbon made of Titanium and steel 1010	FC-72, 101.3 kPa	Steady	Etched steel 1010 with lower roughness in H ₂ SO ₄ liquid	CHF increase 29 %
Hanley, et al.	Nanosmooth sapphire ribbon heaters	Water	Steady	Wettability improve in a porous structure	CHF increase 50-60 %
Tachibana	Flat plate of nickel	Water	Transient	Not discussed	CHF increase at short period
Fukuda, et al.	Platinum and gold horizontal cylinders	Water, 101.3-2063 kPa	Transient 2 ms-20 s	Commercial, rough and smooth surface	CHF occurs at boiling incipience
Fukuda and coworkers	Platinum and gold horizontal cylinders	Various liquid	Transient 2 ms-20 s	Commercial and rough surface	CHF decrease for smooth Surface, CHF occurs at boiling incipience

Berenson [46] reported CHF was independent of modified surface condition.

However, Golobič and Ferjančič [47] conducted experiments using different types and thickness of enhanced coated surface. They used horizontal vertically oriented ribbon heaters made of Ti and Steel 1010 under saturated pool boiling in FC-72 at atmospheric pressure. It was found that even surface roughness can increase CHF by 6 to 12% in FC-72. However, etched Steel 1010 with lower roughness in H₂SO₄ acid could increase CHF by 29 %. The CHF ratio of enhanced coated surface to a ribbon heater with a standard surface is up to 2.3.

Moreover, Ramilison, et al. [48] correlated CHF was surface roughness and contact angle of flat heaters. To correlate, they use the data obtained from Berenson, Lienhard and Dhir and Ramilison. The ranges of surface roughness (RMS) and contact angle are from 2 μm to 12 μm and 0° - 15° , respectively. The following correlation is yielded.

$$q_{cr,sat} = 0.0336(\pi - \theta)^{3.0} R_q^{0.125} \times q_{cr,sat,Z} \quad (2.48)$$

Hanley, et al. [49] examined the separate effects of surface wettability, roughness and porosity on CHF using engineered surfaces. They were prepared on nanosmooth sapphire heaters. The experiments were conducted in pool boiling facility at saturated condition at atmospheric pressure. Roughness was controlled by fabrication of micro-posts having diameter of 20 μm and height of 15 μm . Wettability was controlled by deposition of thin non-porous compact coatings which was made of hydrophilic SiO₂ (typically 20 nm thick) and hydrophobic fluorosilane (monolayer thickness). Porosity and pore size were controlled by deposition of porous layer-by-layer coatings made of SiO₂ nanoparticles. The explored values were found as follows: roughness (R_z) is 0–15 μm , wettability is 0° – 135° and 0–50 % and 50 nm pore size, respectively. It was occurred that porosity strongly affects CHF. Moreover, it was occurred that a combined with hydrophilicity and a porous structure on the boiling surface enhanced CHF by 50-60%. However, when a coupled with hydrophobic surface and porosity resulted in a reduction of CHF by 97 % compared to the reference surface. Hydrophilicity and hydrophobicity had little effect on CHF on a smooth non-porous surface. Surface roughness did not show significant effect on CHF.

2.4.3 Combined hydrodynamic and non-hydrodynamic aspect of CHF

Kandlikar [50] postulated a theoretical model of CHF which incorporates the effects of surface orientation and contact angle. His model is based on a force equilibrium on a vapor bubble on a smooth inclined heated surface. He pointed out that the CHF increases with the decrease of contact angle. In this regard, Okawa, et al. [51] observed that the bubble departure rate increases with the decreasing value of contact angle. On the other hand, the bubble slid up the vertical surface for a long distance.

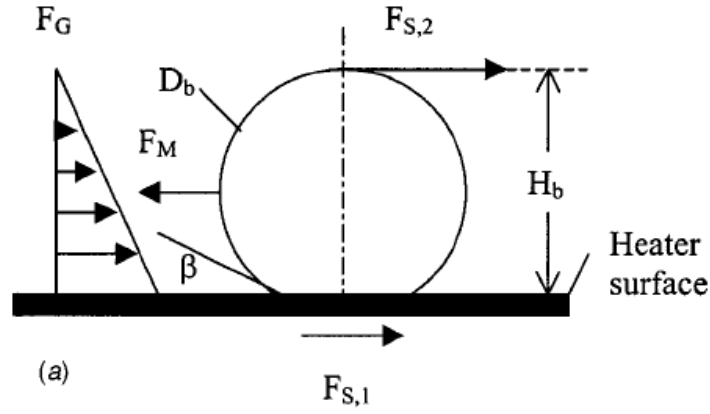


Fig. 2.22 Forces due to surface tension, gravity and momentum acting on a bubble parallel to the heater surface

The force equilibrium on a vapor bubble on a smooth inclined heated surface as shown in Fig. 2.22 according to the Kandlikar et al. is given as

$$F_M = F_{S,1} + F_{S,2} + F_G \quad (2.49)$$

where, $F_{S,1}$ and $F_{S,2}$, are surface tension force at the bubble base, surface tension force at the bubble top, respectively, as follows.

$$F_{S,1} = \sigma \cos \theta \quad (2.50)$$

$$F_{S,2} = \sigma \quad (2.51)$$

F_M and F_G force due to change in momentum and hydraulic pressure gradient due to gravity.

$$F_M = \frac{q_I H_b \cdot 1}{h_{lv}} \frac{q_I}{h_{lv}} \frac{1}{\rho_v} = \frac{1}{\rho_v} \left(\frac{q_I}{h_{lv}} \right)^2 H_b \quad (2.52)$$

$$F_G = \frac{1}{2} g(\rho_l - \rho_v) H_b \cdot H_b \cdot 1 \cdot \cos \phi \quad (2.53)$$

$$H_b = \frac{D_b}{2} (1 + \cos \theta) \quad (2.54)$$

$$q_I = h_{lv} \rho_v^{1/2} \left[\frac{\sigma(1 + \cos \theta)}{H_b} + \frac{1}{2} g(\rho_l - \rho_v) H_b \cos \phi \right] \quad (2.55)$$

$$q_{CHF} = \frac{(1 + \cos \theta)}{16} q_I \quad (2.56)$$

$$q_{CHF} = h_{lv} \rho_v^{1/2} \frac{(1 + \cos \theta)}{16} \left[\frac{2\sigma}{D_b} + g(\rho_l - \rho_v) \frac{D_b}{4} (1 + \cos \theta) \cos \phi \right]^{1/2} \quad (2.57)$$

$$\lambda_T = C_1 2\pi \left[\frac{\sigma}{g(\rho_l - \rho_v)} \right]^{1/2} \quad (2.58)$$

$$C_1 = 1 \quad (2.59)$$

$$D_b = \lambda_T / 2 \quad (2.60)$$

$$q_{CHF, Kandlikar} = \left(\frac{1 + \cos \theta}{16} \right) \left[\frac{2}{\pi} + \frac{\pi}{4} (1 + \cos \theta) \cos \phi \right]^{1/2} h_{lv} \rho_v^{1/2} [\sigma g(\rho_l - \rho_v)]^{1/4} \quad (2.61)$$

where, θ is dynamic receding contact angle. The above equation is valid for upward-facing surface between horizontal and vertical orientations.

2.4.4 Transient CHF

Transient boiling regimes are present in many industrial situations: cooling down of hot surfaces, chill down of pipes by cryogenic propellant before space engines re-ignition and also in accidental situations in the nuclear power plant [8].

Tachibana, et al. [52] tested CHF on transient power condition due to linear heat generation rate have been investigated using horizontal vertically oriented ribbons in water. It was occurred that a clear peak of CHF was found in the region of shorter period. The CHF increases with the increase of power transient, while with lowering rate, the CHF approaches a CHF level particular to steady boiling. The mechanism of high CHF was occurred due to rapid formation and evaporation of thin liquid film at the bases of vapor bubbles.

Transient boiling of water under exponentially escalating heat fluxes has been studied since the 1950. Most of these investigations were carried out in pool boiling conditions, using ribbon and wire heaters. [23]

Fukuda, et al. [28] have carried out transient CHF due to exponentially increasing heat inputs on 1.2-mm horizontal cylinders with commercial surface, mirror-finished surface and Emery 3-finished rough surface in a pool of water for subcoolings and pressures. Moreover, they have carried out the two conditions of pre-pressurization before each experimental run. At short period, CHF was occurred at boiling initiation with explosive boiling leading to film boiling due to heterogeneous spontaneous nucleation (HSN). Fig. 2.23 shows the CHF for various period on 1.2 mm diameter horizontal cylinder in saturated water at various pressures for with and without pre-pressurization for commercial surface. CHF due to HSN which can be seen at short period mainly for with pre-pressurization.

Figure 2.24 shows the CHF for various period on 1.2 mm diameter horizontal cylinder with mirror surface in saturated condition at various pressures and subcooling of 60 K at 690 kPa in water for without pre-pressurization. The CHF due to HSN was occurred for the condition of without pre-pressurization as well as as shown in Fig. 2.24.

They revealed that transient CHF can be divided into three groups, namely, the first group, the second group and the third group as shown in Fig. 2.23. The mechanism

responsible for the first group will be depend on not only hydrodynamic instability (HI) but also heterogeneous spontaneous nucleation. The second group mainly depends on heterogeneous spontaneous nucleation (HSN).

They postulated the CHF correlations for the first and second groups which are corresponding to the HI and HSN as follows.

$$q_{cr} = q_{cst,sub}(1 + 0.21\tau^{-0.5}) \quad (2.62)$$

$$q_{cr} = q_{cst,sub}(1 + 0.023\tau^{-0.7}) \quad (2.63)$$

$$q_{cr} = h_c(\Delta T_i(\tau) + \Delta T_{sub}) \quad (2.64)$$

$$h_c = \left(\frac{k_l \rho_l c_{pl}}{\tau} \right)^{1/2} \quad (2.65)$$

The symbol of h_c is the heat transfer coefficient resulting from transient heat conduction, $\Delta T_i(\tau)$ is the initial boiling surface superheat due to HSN in conduction regime, and ΔT_{sub} is liquid subcooling.

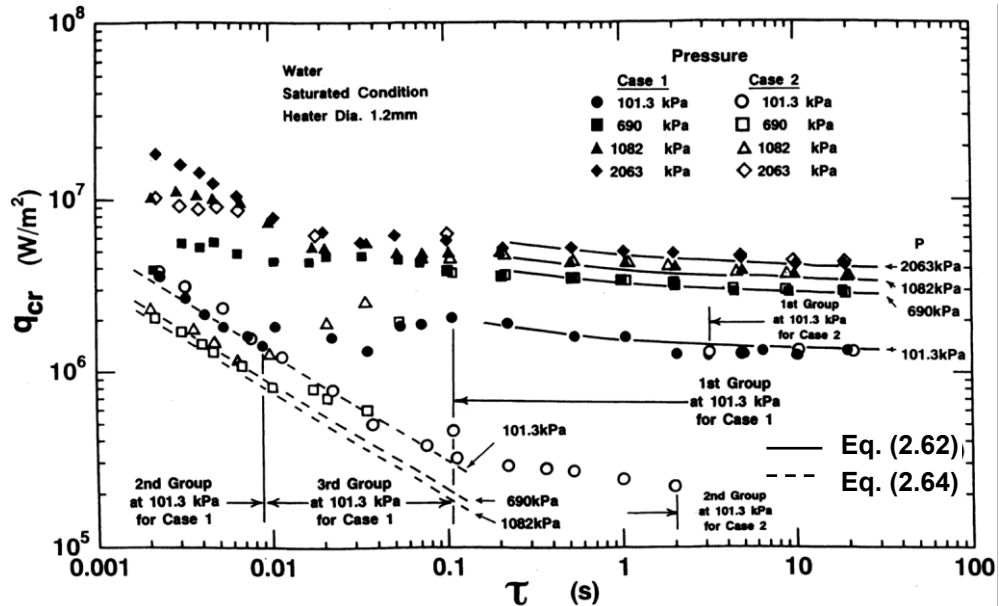


Fig. 2.23 The transient CHF for period due to with and without pre-pressure for commercial surface

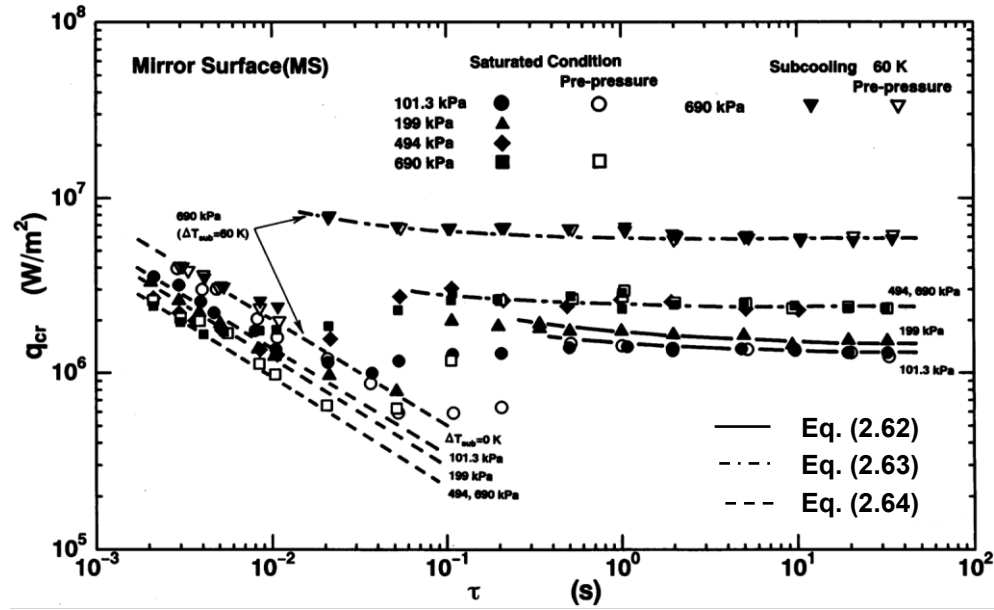


Fig. 2.24 The transient CHF for period due to with and without pre-pressure for mirror surface

Fukuda and coworkers [28-35] have conducted transient CHF due to various exponentially increasing heat inputs on horizontal for various liquids such as non-wetting liquid, water, and wetting liquids such as liquid nitrogen, ethanol, liquid helium, R-113 and FC-72 for wide ranges of pressures and subcooling.

However, they have unexamined the relationship of transient CHF and contact angle.

Chapter 3

Experimental Apparatus, Method and Procedure

In this chapter, the pool boiling experimental apparatus, the test section, experimental method and procedure with heat input control system and data processing are described in order to study pool boiling heat transfer, the critical heat flux (CHF) and vapor behavior due to exponentially increasing heat inputs on a horizontal cylinder in subcooled boiling water for without and with pre-pressurization before each experimental run.

3.1 Treatment of test heater

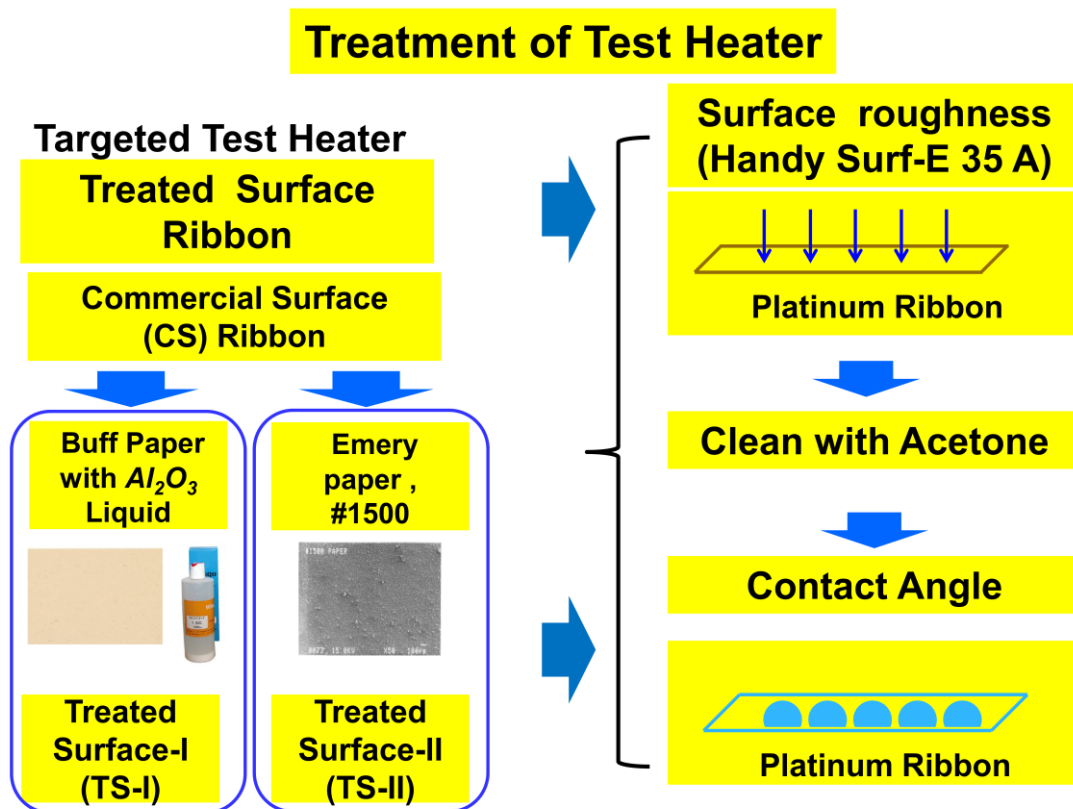


Fig. 3.1 Treatment of test heater

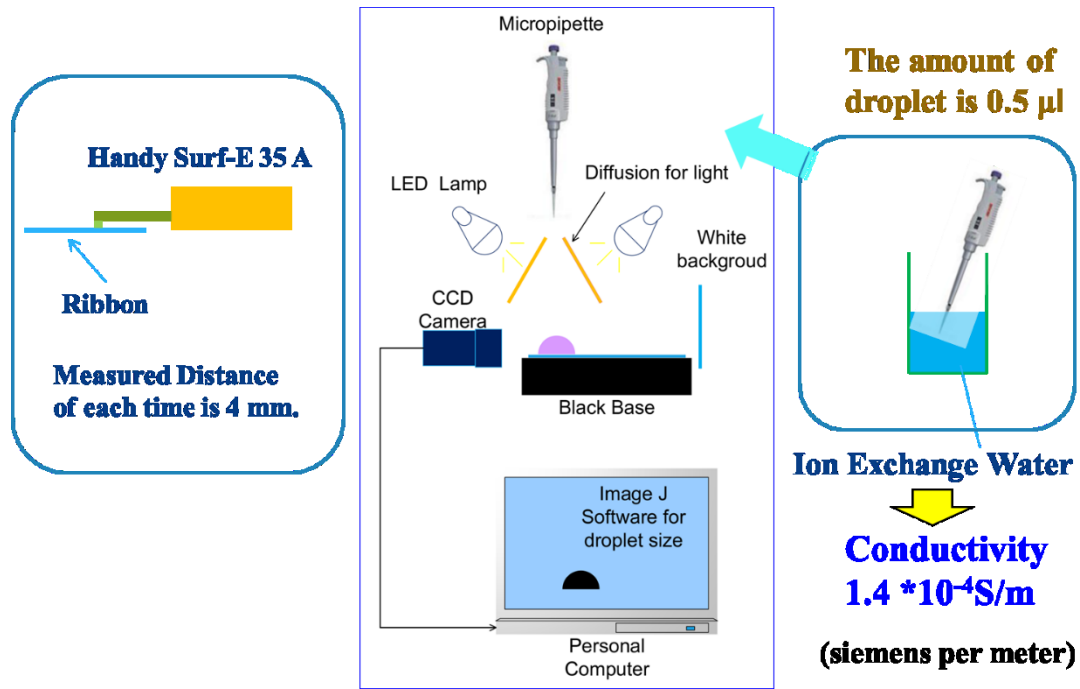


Fig. 3.2 Measurement of surface roughness and contact angle

In this study, we have prepared the three kinds of heaters having the heater dimension of width, thickness and effective length ($4 \times 0.1 \times 30$) mm, ($4 \times 0.1 \times 30$) mm and ($4 \times 0.2 \times 41$) mm, respectively for CS, TS-I and TS-II. Figure 3.1 shows treatment of test heater for the TS-I and TS-II which were treated from commercially available ribbon to obtain the targeted treated surface. The former was finished with buff paper together with alumina, Al_2O_3 suspension (average particle size of $0.3 \mu\text{m}$). The latter was done by emery paper with granularity of #1500.

Figure 3.2 shows the measurement of surface roughness and contact angle for heaters. The surface roughnesses were measured perpendicularly by a profilometer, the Handysurf-E-35-A, at uniformly distributed different five places on a surface of platinum ribbon. The measurable distance of the profilometer is 4 mm in a time. The heaters were cleaned with acetone ($\text{C}_3\text{H}_6\text{O}$). An ion-exchange-water droplet with an amount of $4 \mu\text{m}$ after distillation was put on one of the places where surface roughnesses were previously carried out with the aid of the autoclavable pipettor ($0.5\text{-}10 \mu\text{l}$) to measure the contact angle. It was performed in room temperature. Then, the image of the droplet was attained immediately by together with CCD camera (Nikon, Japan) and Ulead image-capturing

software which was installed in personal computer. Similar attempts were carried out up to five droplets. The actual dimensions of each droplet were measured for five times by AutoCAD software.

The contact angle, θ , was calculated by Eq. (3.1) in Honjo, et al.,[53]. For each droplet, the contact angle value (average of five measurements) was implemented. The schematic of measurement of contact angle, θ , is shown in Fig. 3.3 [53] .

$$\theta = 2\theta_1 = 2 \cdot \tan^{-1}(h/b) \quad [^\circ] \quad (\text{or})$$

$$\theta = 2\theta_1 = \pi/90 \tan^{-1}(h/b) \quad [\text{rad}] \quad (3.1)$$

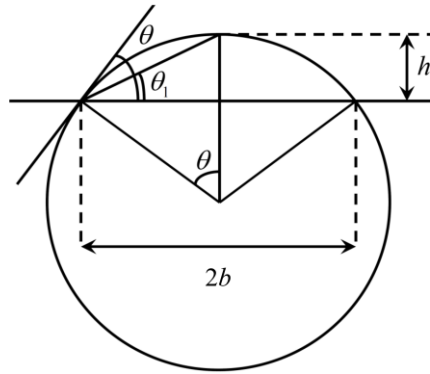
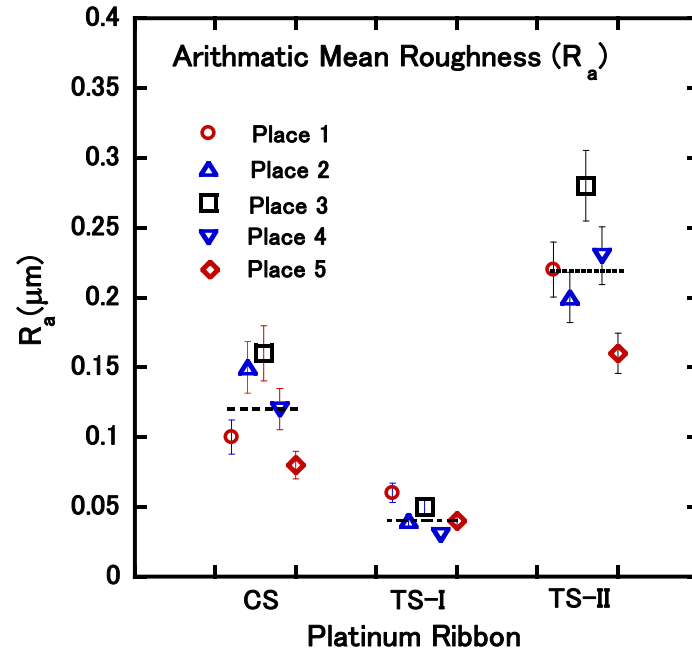


Fig. 3.3 The method for measurement of contact angle (θ)

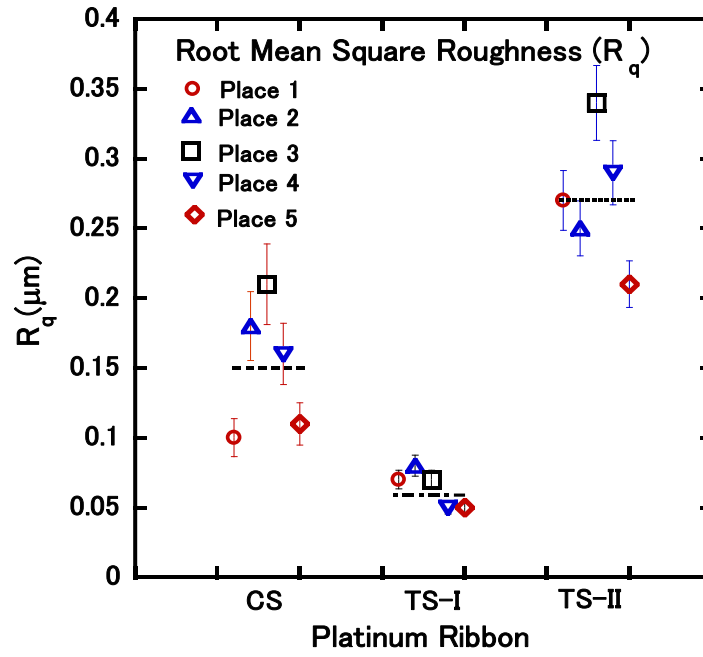
3.2 Results of surface roughness and contact angle

Figures 3.4 (a) and (b) show the values of arithmetic mean roughness, R_a , and root mean square roughness, R_q , which are the averages of five readings at five places measured on CS, TS-I and TS-II, respectively. The TS-II has the largest roughness value and TS-I has the smallest one in this study. The values of R_a for the CS, TS-I and TS-II are $0.1 \pm 0.015 \mu\text{m}$, $0.04 \pm 0.005 \mu\text{m}$ and $0.22 \pm 0.02 \mu\text{m}$, respectively. Moreover, the results of R_q are $0.152 \pm 0.021 \mu\text{m}$, $0.06 \pm 0.006 \mu\text{m}$ and $0.27 \pm 0.02 \mu\text{m}$, respectively.

Figure 3.5 shows the values of contact angle, θ , measured on the CS, TS-I and TS-II. TS-II has the smallest contact angle value and TS-I has the largest one. The values of contact angle, θ , which are the averages of five droplets of the test heaters of CS, TS-I



(a)



(b)

Fig. 3.4 The values of surface roughness (a) R_a and (b) R_q of CS, TS-I and TS-II

and TS-II are $60.6 \pm 1.3^\circ$, $62.0 \pm 1.0^\circ$ and $51.47 \pm 0.7^\circ$, respectively. In addition, the typical

results of surface roughnesses, R_a , R_q and contact angle, θ , values for those heaters are indicated in Figs. 3.6 and 3.7, respectively.

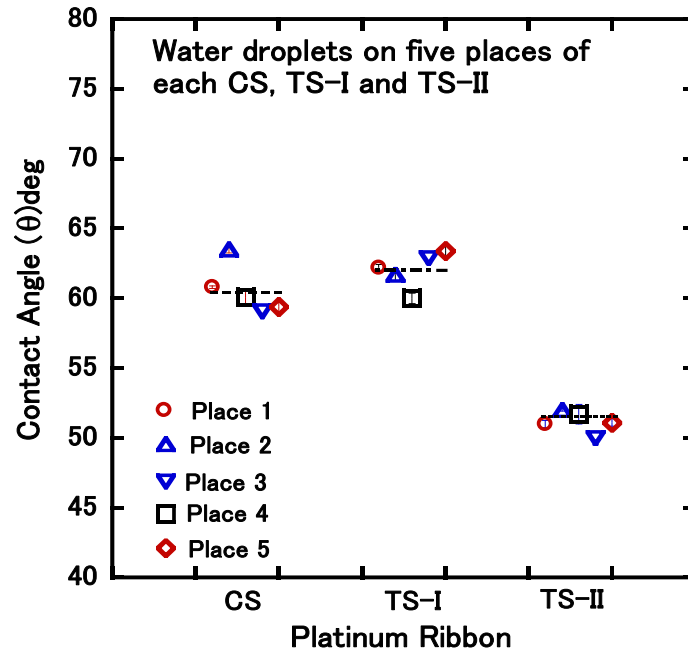
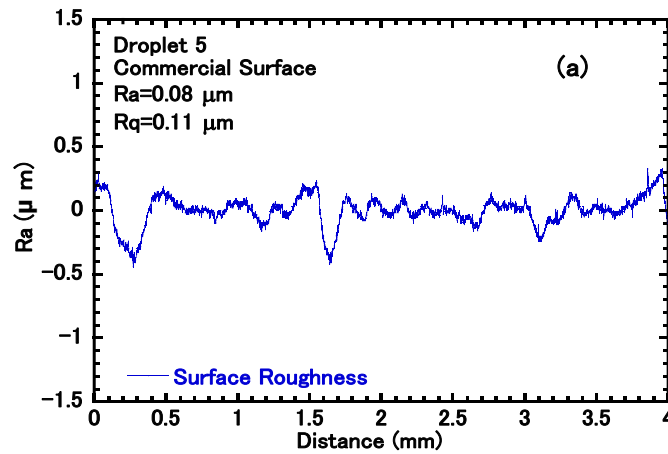


Fig.3.5 The values of contact angle, θ , of droplets on CS,TS-I and TS-II



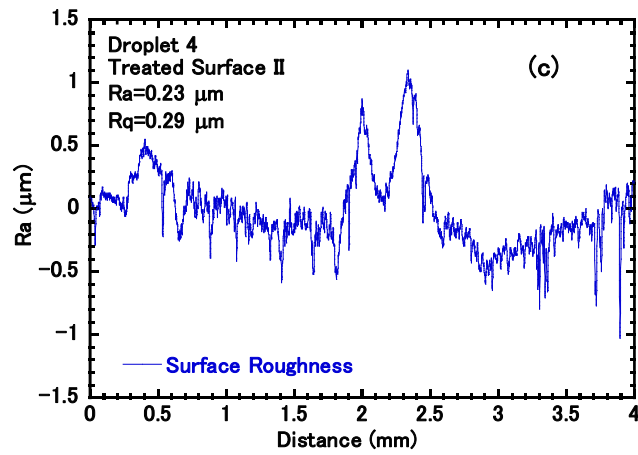
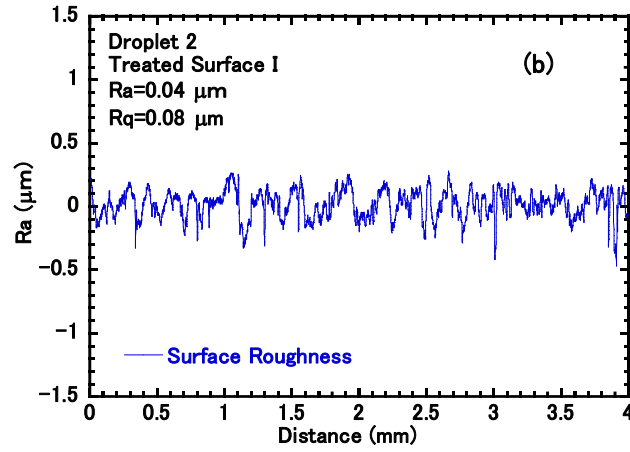


Fig.3.6 Typical results of R_a and R_q of (a) CS, (b) TS-I and (c) TS-II

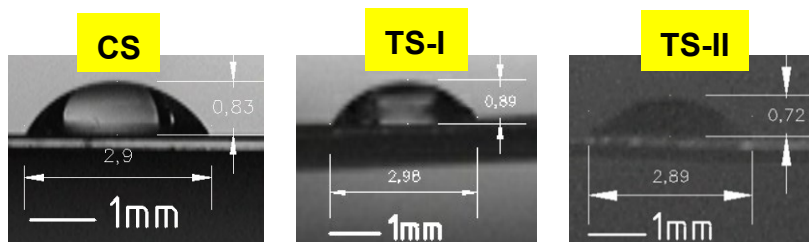
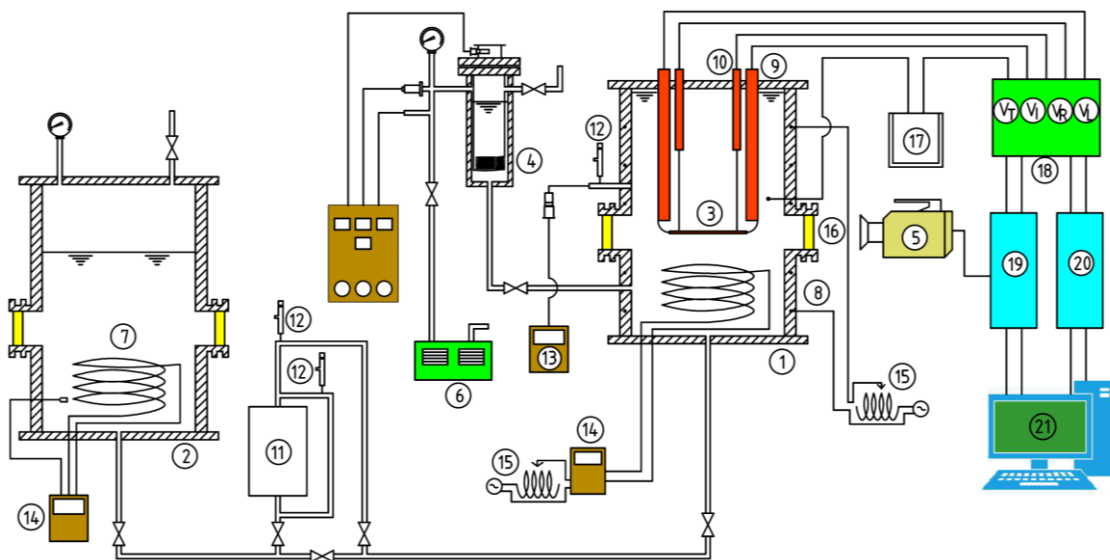


Fig. 3.7 Typical water droplets on the surface of CS, TS-I and TS-II

3.3 Experimental pool boiling apparatus

The experimental pool boiling apparatus is shown in Fig. 3.8. It is mainly comprised of a boiling vessel (1), a test section including horizontal vertically oriented platinum ribbon heater (3), a pressurizer (4), heating system (18), and a data measurement and processing system (19)-(21), and a video camera system (5). The boiling vessel is made of cylindrical stainless steel with 20-cm inner diameter and 60-cm height capable of operating up to 5 MPa. The two current conductors and two potential conductors were installed at the upper side of the vessel, which were also used to support the test heater. The vessel has two observation windows and is equipped with a pressure transducer and a sheathed 1-mm diameter K-thermocouple that is used to measure the bulk liquid temperature.



- | | | |
|--------------------------|-----------------------------|----------------------------|
| (1) Boiling Vessel | (2) Auxiliary Tank | (3) Experimental Heater |
| (4) Pressurizer | (5) Video Camera | (6) Vacuum Pump |
| (7) Sheathed Heater | (8) Microheater | (9) Current Conductor |
| (10) Potential Conductor | (11) Pressure Pump | (12) Pressure Relief Valve |
| (13) Pressure Gauge | (14) Temperature Controller | (15) Slide rheostat |
| (16) Observation Window | (17) Cold Junction | (18) Heating System |
| (19) A/D Converter | (20) D/A Converter | (21) Personal Computer |

Fig. 3.8 Pool boiling experimental apparatus

3.4 Test section

The illustrated test section is given in Fig. 3.9. The two Teflon plates supported to current conductors and potential taps. The horizontal vertically oriented treated surface ribbon heater was attached to test section through the copper wires. They are joined by soldering at each end. Two fine $30\text{ }\mu\text{m}$ diameter platinum wires (potential taps) were spot-welded on the heater at about 10 mm from each end of the heater. The effective length of the heater between the potential taps in this study was about 30 mm for CS and TS-I, and 41 mm for TS-II

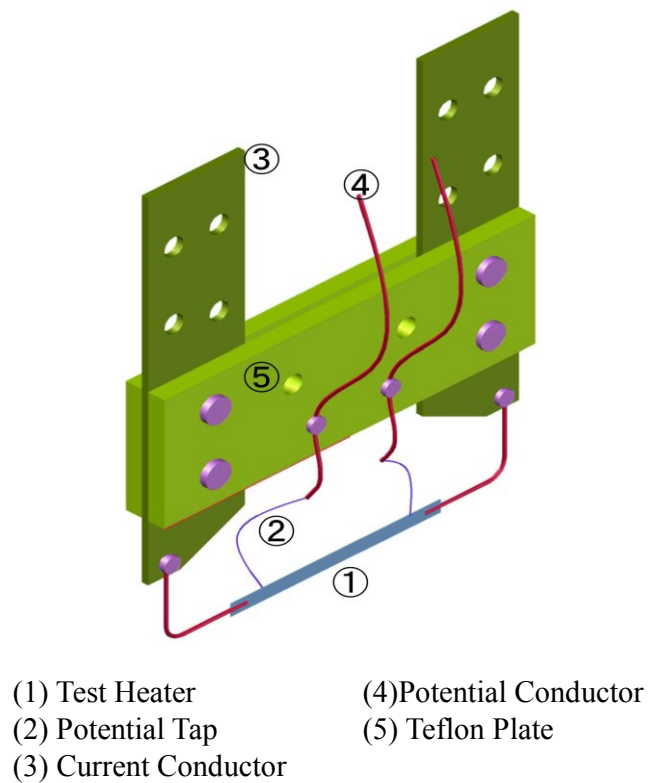
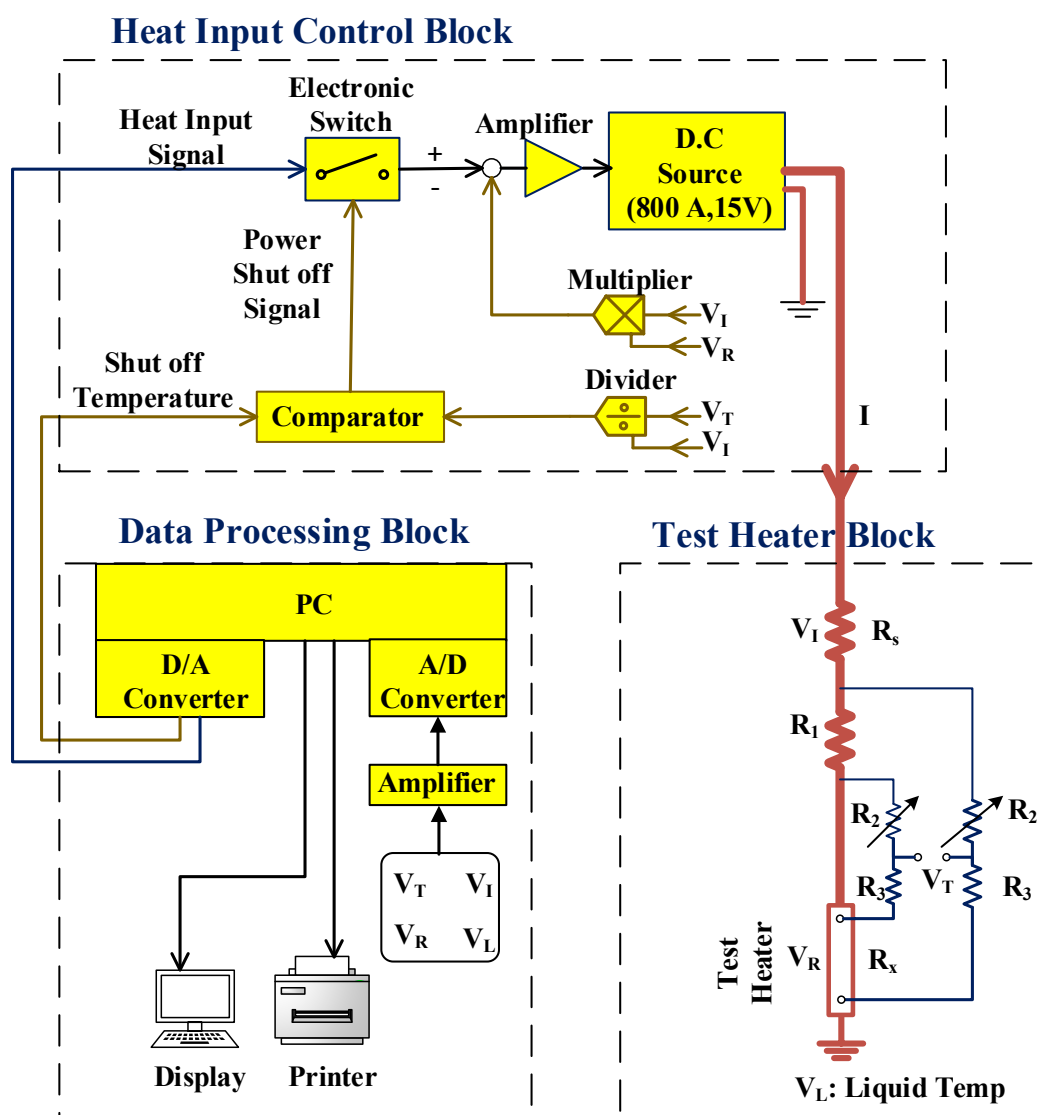


Fig.3.9 Horizontal vertically oriented treated platinum ribbon test heater and test section



digital-to-analog (D/A) converter (CONTEC Co.Ltd., Japan). A fast response, direct current source (800A, 15V) (Takasago, Ltd. Japan) are supplied to test heater. The direct current source was controlled by a personal computer so as to give a desired time function for the heat input by Sakurai and Shiotsu [54-55]. The voltage drops across a standard resistance (V_I), across the potential taps of the heater (V_R) and the output voltages of the double bridge circuit (V_T), were passed to computer via amplifiers (YOKOGAWA, Japan) and analog-to-digital (A/D) converter (CONTEC Co.Ltd., Japan). These voltages were simultaneously monitored at a constant time interval ranging from 60 μ s to 120 ms to evaluate heat generation rate, Q , and average temperature, T_a .

The average temperature, T_a , was attained according to the previously calibrated resistance-temperature relation, $R_T = R_0(1 + \alpha T + \beta T^2)$, where, $R_T(\Omega)$ is resistance in a double bridge circuit (YOKOGAWA, Japan), and R_0 and α are fitted constant. The value of β is -5.88×10^{-7} for Grade-1 annealed platinum at temperatures up to 1500°C by Raymond [56]. The measured resistance-temperature relation of the CS, TS-I and TS-II are described in Fig. 3.11.

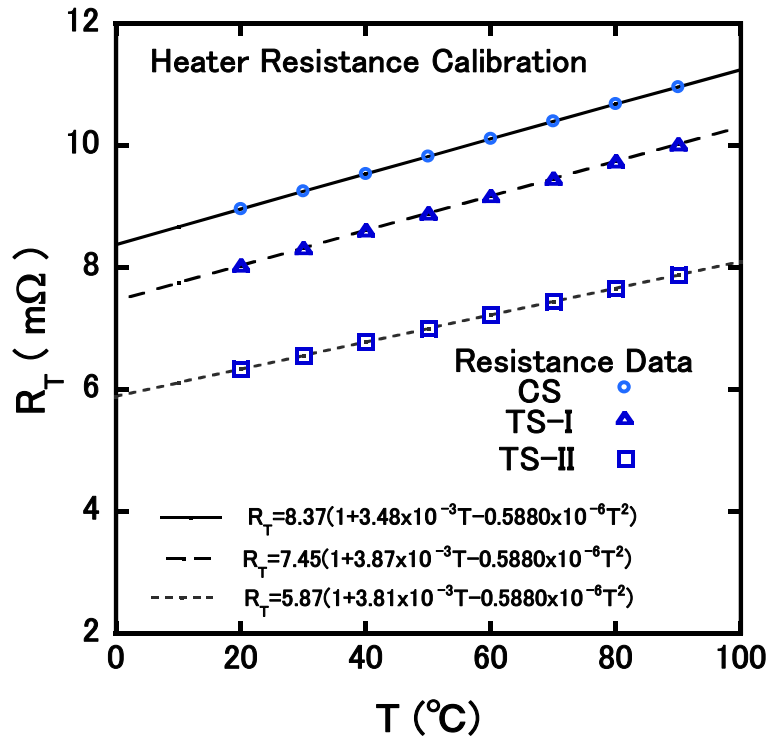


Fig. 3.11 Resistance-temperature relation of the CS, the TS-I and TS-II

The resistance of the test heater in the test heater block in Fig. 3.10 is given as follow,

$$R_x = \frac{R_1 R_3 + \frac{V_T}{I} (R_3 + R_2)}{R_2} \quad (3.2)$$

If the average temperature is higher than shut off temperature which have already set up in computer, the power shut off signal was sent to electronic switch to cut out the power supply not to occur actual burnout of the heater.

The heat generation rate of the heater, Q , was determined by the multiplication of the current to heater, I , and the voltage difference between potential taps of the heater, V_R . According to this relation, as heat generation rate will change simultaneously with resistance change of test heater in the transient and steady-state boiling, a heat generation control system have been developed. In this system, the heat generation rate and the temperature of test heater were calculated and the heat generation rate according to the $Q = Q_0 \exp(t/\tau)$ was simultaneously controlled by a personal computer. Moreover, the heat generation rate can be calculated by the following equation,

$$Q = V_R \frac{V_I}{R_s} \quad (3.3)$$

The heat flux, q , of the heater during experiment is computed by the difference between the heat generation rate per unit surface area, Q , and the rate of change of energy storage in the heater as follows:

$$q = \frac{\delta}{2} \left[Q - \rho_h c_h \frac{dT_a}{dt} \right] \quad (3.4)$$

where ρ_h , c_h and δ are the density, the specific heat and the half thickness of heater, respectively. The half thickness of heater was used because boiling occurred on both sides of heater. The average temperature, T_a , was attained at the faired average temperature versus time curve.

The surface temperatures between the two potential taps, T_s , were obtained by solving the unsteady heat conduction equation of the heater under the conditions of the average temperature, T_a , and the heat generation rate per unit area, Q , of the test heater as follows:

$$\left. \frac{dT}{dt} \right| = a \frac{d^2T}{dx^2} + \frac{Q}{\rho_h c_h} \quad (3.5)$$

The following boundary conditions are given to numerically analyze the unsteady equation.

$$\left. \frac{dT}{dx} \right|_{x=0} = 0, \quad -k \left. \frac{dT}{dx} \right|_{x=\delta/2} = q \quad (3.6)$$

$$T_a = \frac{\int_0^{\delta/2} T dx}{\int_0^{\delta/2} dx} = \frac{2}{\delta} \int_0^{\delta/2} T dx \quad (3.7)$$

Ion-exchange-distilled water was fully filled in the boiling vessel with the free surface only in the pressurizer and auxiliary tank. Then, the liquid in each tank is separately heated by sheathed heaters installed in each tank. Every tank was degassed by keeping it boiling for 30 minutes at least. The liquid temperatures in the boiling vessel and pressurizer were separately controlled to acquire the desired saturated and subcooled conditions. The vessel was kept warm by micro heater and insulated by lagging materials. For the pre-pressure, the vessel was pressurized up to 2 MPa with reciprocating pump with a diaphragm (Nikkiso, Japan) before each experimental run.

The exponential function, $Q = Q_0 \exp(t/\tau)$, where, t means time and τ means exponential period, was selected for the heat input. CHF was determined at a start point where an average temperature rapidly increases up to the preset temperature which is controlled by a burnout detector.

3.6 Uncertainty analysis

The uncertainty analysis was carried out for mainly for the measurement error or precision error, notation in S , and the data acquisition system error or bias error, notation in B . The error of data acquisition system is considered uniform (rectangular) distribution [57-59]. The general form of uncertainty due to uniform distribution is given as follow,

$$u = \frac{a}{\sqrt{3}} \quad (3.8)$$

where, a can be errors in instrument, data acquisition system, precision, random, and so on.

Moreover, the experimental results of pressure, liquid temperature, heat generation rate, heater surface temperature and heat flux. They were listed in Table 3.1.

Table 3.1 Uncertainty analysis of pressure, liquid temperature, average temperature, heat generation rate and heat flux.

Parameter	Maximum Operation Range	Maximum Permissible Error (%)	Uncertainty
Heat Generation	$3 \times 10^{11} \text{ W/m}^3$	$\pm 1 \%$	$\pm 3.0 \times 10^9 \text{ W/m}^3$
Heat Flux,	$0 - 3.2 \times 10^6 \text{ W/m}^2\text{K}$	$\pm 1.2 \%$	$\pm 0.0384 \times 10^6 \text{ W/m}^2\text{K}$
Average Temperature	$0 - 440 \text{ K}$	$\pm 0.05 \%$	$\pm \sim 1 \text{ K}$
Liquid Temperature	$0 - 406.2 \text{ K}$	$\pm 0.05 \%$	$\pm \sim 1 \text{ K}$
Pressure	5000 kPa	$\pm 0.11 \%$	$\pm 5.78 \text{ kPa}$

The listed uncertainties were estimated by the following equations. The uncertainty of heat generation rate, u_Q , is given in Eq. (3.9) as,

$$u_Q = \frac{B_Q + S_Q}{\sqrt{3}} \quad (3.9)$$

where, B_Q and S_Q are the errors of data acquisition system and precision error, respectively. They were also obtained as follows,

$$B_Q = \frac{\left(\frac{\partial Q}{\partial V_I} \right) \left(\frac{B_{V_I}}{V} \right) + \left(\frac{\partial Q}{\partial V_R} \right) \left(\frac{B_{V_R}}{V} \right)}{\sqrt{3}} \quad (3.10)$$

$$S_Q = \frac{\left(\frac{\partial Q}{\partial V_I}\right)\left(\frac{S_{V_I}}{V}\right) + \left(\frac{\partial Q}{\partial V_R}\right)\left(\frac{S_{V_R}}{V}\right)}{\sqrt{3}} \quad (3.11)$$

where, B_{V_I} and B_{V_R} errors of amplifier (YOKOGAWA,3131, Japan), respectively. S_{V_I} and S_{V_R} are measured precision errors. The value of V is taken as respective measured value in the experimental result.

The general form of precision error is given in Eqs. (3.12) and (3.13) as follows,

$$S = \sqrt{\frac{\sum_{i=1}^N \left(x_i - \bar{x}\right)^2}{N-1}} \quad (3.12)$$

$$S_{\bar{x}} = \frac{S}{\sqrt{N}} \quad (3.13)$$

The uncertainty of heat flux, u_q , is obtained as,

$$u_q = \frac{u_Q + u_{T_a}}{\sqrt{3}} \quad (3.14)$$

where, u_{T_a} is the error of average temperature and it is obtained by the following equations,

$$u_{T_a} = \frac{B_{T_a} + S_{T_a}}{\sqrt{3}} \quad (3.15)$$

$$B_{T_a} = \frac{w_1\left(\frac{B_{V_T}}{V}\right) + w_2\left(\frac{B_R}{V}\right)}{\sqrt{3}} \quad (3.16)$$

$$S_{T_a} = \frac{w_1\left(\frac{S_{V_T}}{V}\right) + w_2\left(\frac{S_R}{V}\right)}{\sqrt{3}} \quad (3.17)$$

$$w_1 = \frac{u_V}{u_V + u_R} \quad (3.18)$$

$$w_2 = 1 - w_1 \quad (3.19)$$

where, B_{V_T} and B_R are errors of amplifier (YOKOGAWA,3131, Japan) and double bridge (YOKOGAWA,2786, Japan), respectively. The w_1 and w_2 are weight ratio in the amplifier and double given by Shibahara, et al. [60].

Equations (3.20) and (3.21) are uncertainties in the amplifier and double bridge, u_V and u_R , respectively, for the estimation of average temperature according to [60].

$$u_V = \frac{\left(\frac{B_{V_T}}{V}\right) + \left(\frac{S_V}{V}\right)}{\sqrt{3}} \quad (3.20)$$

$$u_R = \frac{\left(\frac{B_R}{R}\right) + \left(\frac{S_R}{R}\right)}{\sqrt{3}} \quad (3.21)$$

The uncertainty of pressure, u_P , is obtained as the Eq. (3.22),

$$u_P = \frac{B_{V_p} + B_{V_g}}{\sqrt{3}} \quad (3.22)$$

where B_{V_p} and B_{V_g} are errors in pressure transducer (KYOWA, PG-50 KU, Japan) and Kyowa amplifier (WGA-710), respectively.

Moreover, the uncertainty of liquid temperature, u_{T_l} , is given as follow,

$$u_{T_l} = \frac{B_K + B_{V_L}}{\sqrt{3}} \quad (3.23)$$

where, B_K is error in K-Thermocouple, $\pm 0.004C^\circ$ between $373C^\circ - 1000C^\circ$. B_{V_L} is error in amplifier (YOKOGAWA,3131, Japan).

Chapter 4

Transient Boiling Critical Heat Flux on Different Surfaces in Pool of Water

4.1 Experimental conditions

The experimental conditions to obtain the heat transfer processes and CHF's that caused by exponentially increasing heat inputs on horizontal vertically oriented ribbon heaters are described in Table 4.1.

Table 4.1 Experimental conditions of transient boiling critical heat flux on horizontal vertically oriented ribbon heater with treated surface condition in pool of water

Parameter	CS	TS-I	TS-II
Liquid	Water	Water	Water
Heat Input (Q)	$Q_{0\exp}(t/\tau)$	$Q_{0\exp}(t/\tau)$	$Q_{0\exp}(t/\tau)$
Pressure (P)	101.3 kPa	101.3 ~ 297 kPa	101.3 kPa
Subcooling (ΔT_{sub})	0 K	0 ~ 20 K	0 K
Period (τ)	5 ms ~ 5 s	5 ms ~ 20 s	26 ms ~ 20 s
Pre-pressure	0 MPa	0 MPa	0 MPa & 2 MPa
Material	Platinum	Platinum	Platinum
L (length)	30 mm	30 mm	41 mm
W (Width)	4 mm	4 mm	4 mm
$2 \times \delta$ (Thickness)	0.1 mm	0.1 mm	0.2 mm
R_a	$0.12 \pm 0.015 \mu\text{m}$	$0.04 \pm 0.005 \mu\text{m}$	$0.22 \pm 0.02 \mu\text{m}$
R_q	$0.15 \pm 0.021 \mu\text{m}$	$0.06 \pm 0.006 \mu\text{m}$	$0.27 \pm 0.02 \mu\text{m}$
θ	$60.6 \pm 1.3^\circ$	$62.0 \pm 1.0^\circ$	$51.7 \pm 0.7^\circ$

4.2 Non-boiling heat transfer coefficient

Figure 4.1 shows the typical experimental results of the heat transfer coefficient, h , versus exponential heat generation period, τ , which were measured at atmospheric pressure before boiling initiation. This experiment was carried out at the surface temperature of 383 K and liquid temperature of 353 K. The experimental results are delineated by solid circles. In the figure, h_c , which is shown in broken line represents the corresponding values of the heat conduction correlation as is seen in Eq. (2.65) in Hayashi, et al.[61], h_n , which is illustrated in solid line represents the corresponding values of steady-state natural convection heat transfer correlation in Fujii and Fujii [62] and h_m which is depicted in blue chain-line corresponds to the values of combination of transient conduction and natural convection heat transfer correlation in Sakurai and Shiotsu [54]. As shown in the figure, the transient conduction heat transfer influences as the period shortens, especially in the region of within 200 ms. However, the natural convection heat transfer governs for period over 3.3 s and approaches a constant value to be a quasi-steady-state heat transfer.

The natural convection heat transfer is given as follow,

$$h_n = \frac{k}{H} \left[C^* (Gr_H^* Pr)^{1/5} \right] \quad (4.1)$$

where,

$$C^* = \left[\frac{Pr}{4 + 9 Pr^{1/2} + 10 Pr} \right]^{1/5} \text{ and} \quad (4.2)$$

$$Gr_H^* = \frac{(H^4 g \beta q)}{k \nu^2} \quad (4.3)$$

The combination of natural convection and transient convection is given as follow,

$$h_m = \left[h_c^4 + h_n^4 \right]^{1/4} \quad (4.4)$$

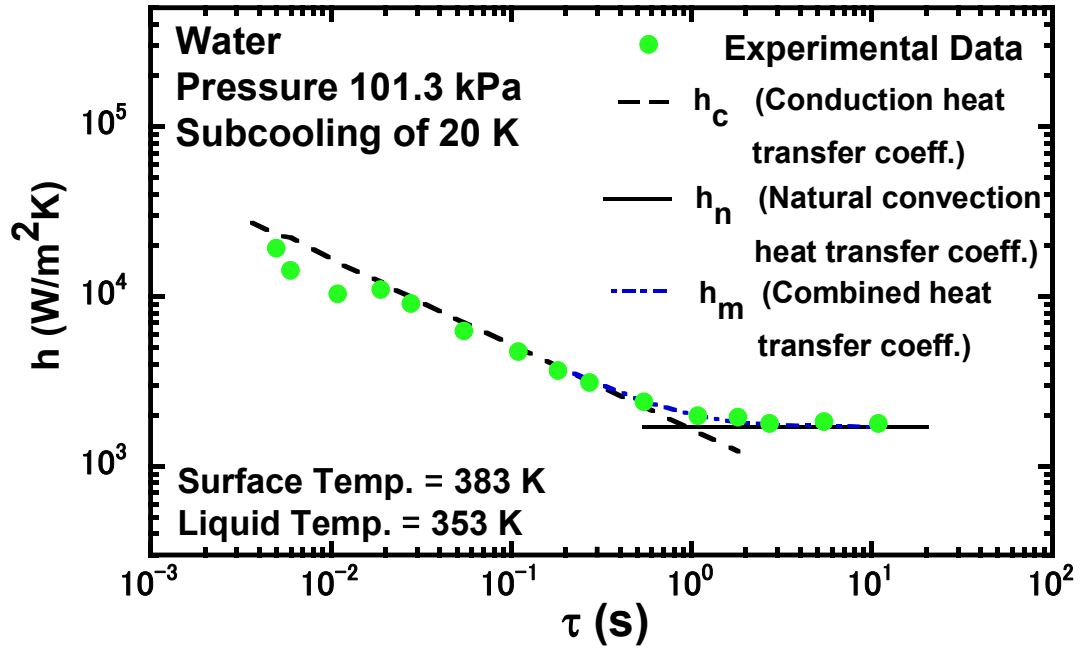
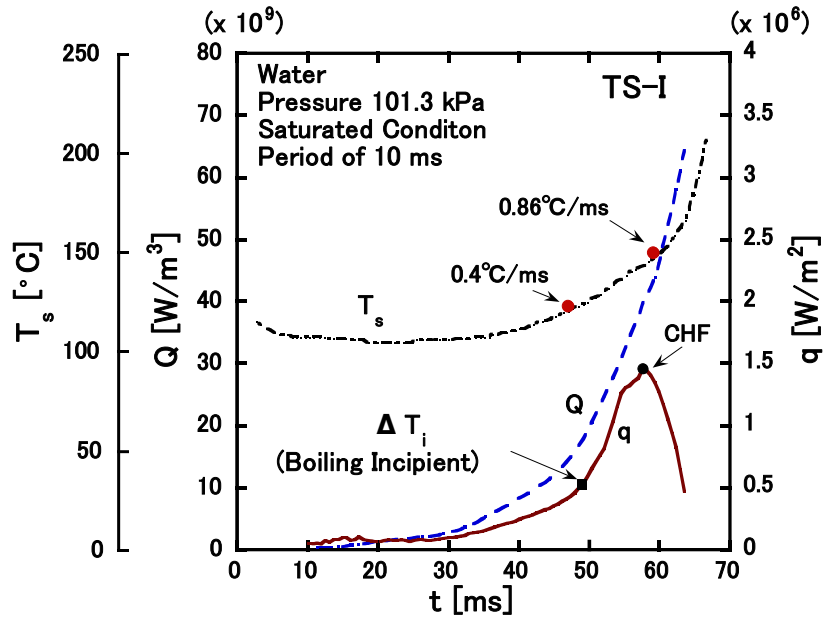


Fig. 4.1 The relation of non-boiling heat transfer coefficient and period, τ , for TS-I

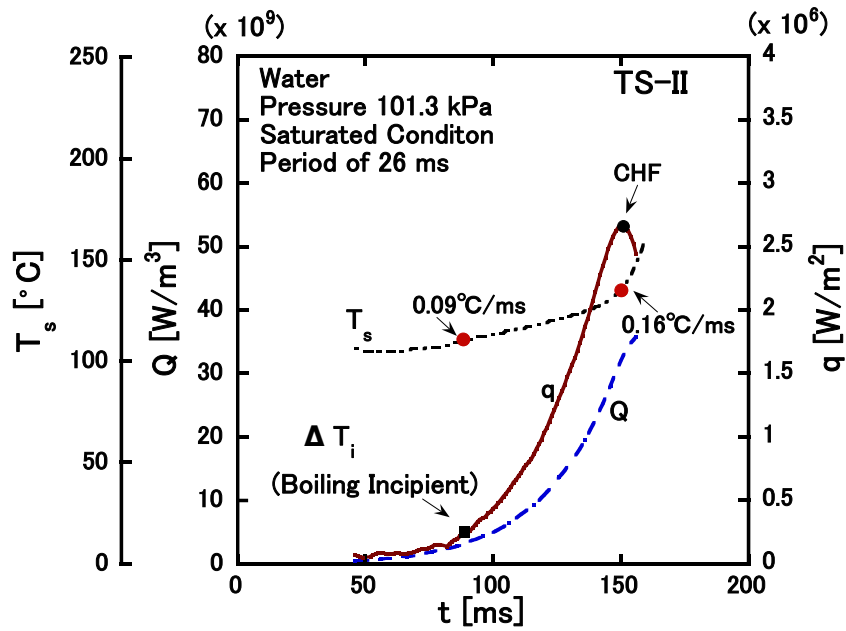
4.3 The time dependence of heat generation rate, heat flux and surface temperature

Figure 4.2 (a) indicates the traces of the heat generation rate, Q , heat flux, q , and surface temperature, T_s , on elapsed time, t , due to exponential increasing heat input for the period, τ , of 10 ms on TS-I in a pool of boiling water at 101.3 kPa. It can be seen that the heat generation, Q , increases exponentially, then the heat flux, q , rapidly increases through a boiling initiation and CHF, respectively, and it decreases rapidly after the CHF. The time taken to reach the CHF of 1.5 MW/m^2 is 58 ms. The surface temperature, T_s , increases slightly before boiling initiation with the increasing rate of $0.4 \text{ }^\circ\text{C/ms}$. However, after boiling initiation, it increases rapidly up to the surface temperature of $150 \text{ }^\circ\text{C}$ with the increasing rate of $0.86 \text{ }^\circ\text{C/ms}$. The rapid increasing rate of the surface temperature appears because the boiling initiation occurs explosively with a nucleate boiling for a while and it is followed by rapid increasing heat input.

The similar trace was carried out for TS-II for the period, τ , of 26 ms at 101.3 kPa under saturated condition as shown in Fig. 4.2 (b). The heat generation, Q , increases exponentially and the heat flux, q , increase along heat generation rate through a boiling initiation and CHF. The time taken to reach the boiling initiation and the CHF are 80 ms



(a)



(b)

Fig. 4.2 The time dependence of heat generation rate, heat flux and surface temperature for (a) TS-I and (b) TS-II

and 149 ms, respectively. The increasing rate of surface temperature before and after the boiling initiation are 0.09 °C/ms and 0.16 °C/ms, respectively, which are lower than

TS-I. However, the heat flux increases to CHF value of 2.7 MW/m² at 137° C.

4.4 Steady-state heat transfer processes under saturated condition

The typical steady-state heat transfer processes in a pool of water for ribbon heater under saturated condition at pressures are shown in Fig. 4.3. The natural convection regime is compared with natural convection equation by Fujii et al. The surface superheats at fully developed nucleate boiling (FDNB) are consistent and independent from pressure. The CHF values obtained by 199 kPa and 297 kPa are same, however, they are higher than that of 101.3 kPa.

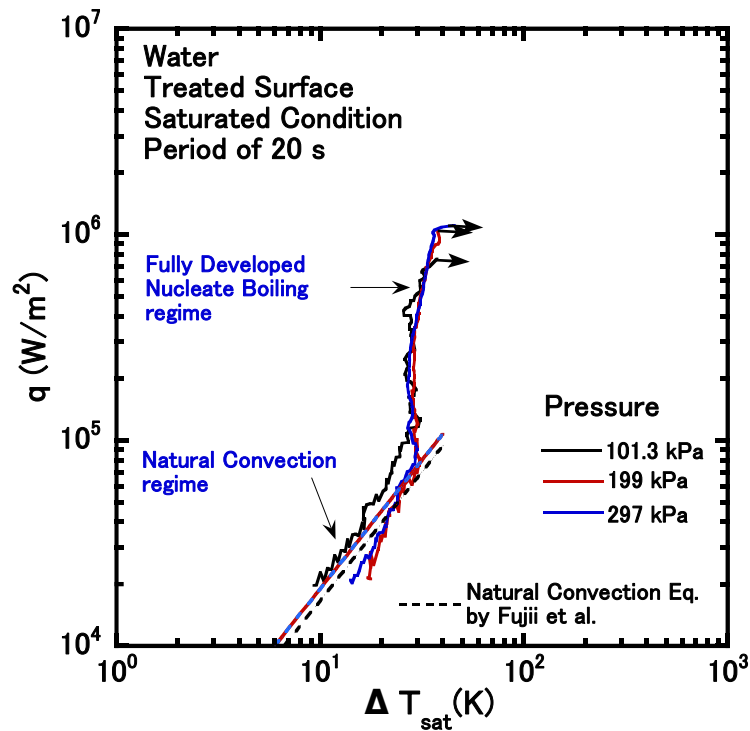


Fig. 4.3 Steady-state heat transfer under saturated condition

4.5 Steady-state heat transfer processes under subcooled condition

Figure 4.4 shows the typical steady-state heat transfer processes in subcooled pool cooling at the pressure 297 kPa and the different subcooling from 0 K to 20 K. The natural convection regimes are compared with natural convection equation as a reference. The CHF values are higher according to the higher subcooling.

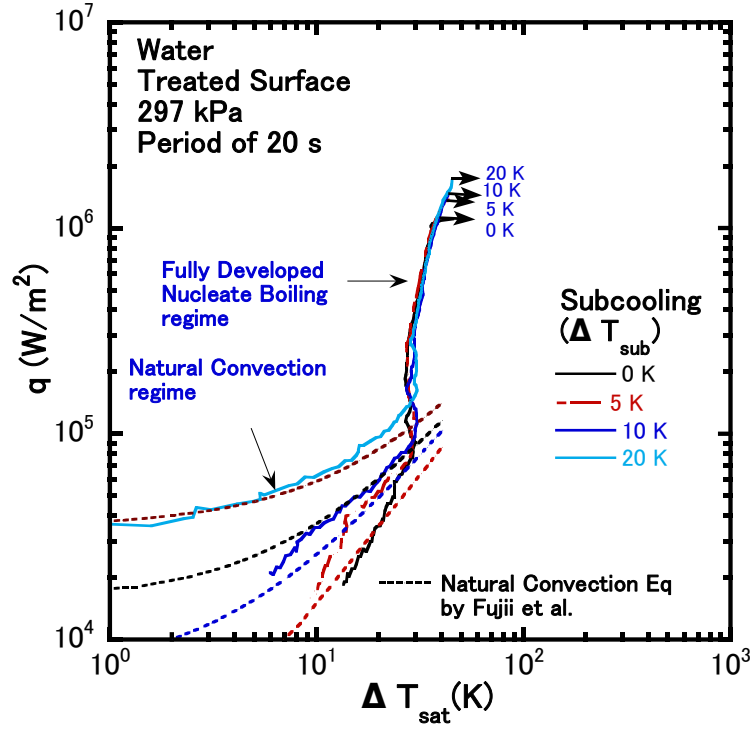


Fig. 4.4 Steady-state heat transfer under subcooled condition

4.6 Steady-state CHF

The steady-state CHF data were measured on a horizontal vertically oriented ribbon heater (TS-I only) in a pool of water due to quasi-steadily heat inputs at the period, τ , of 20 s, for subcoolings with pressure as a parameter are shown in Fig. 4.5. In this figure, the solid marks are the experimental CHF data [16] for pressures at various subcoolings measured on a horizontal vertically oriented platinum ribbon with 5.4 mm-wide (commercial surface). The measured CHF in this study are depicted in hollow markers. The measured CHF data described with hollow markers increase with an increase of subcoolings. The corresponding non-linear subcooled pool boiling CHF data [16] based on hydrodynamic instability (HI) attained by modifying Kutateladze's correlation are described with the solid lines for comparison. They are expressed by Eqs. (2.46) and (2.47), respectively. It was occurred that the experimental CHF data [16] and the non-linear subcooled pool boiling CHF data are higher than our results. The newly empirical equation of CHF, $q_{cr,sub}$, which is independent of pressure based on the measured CHF in this study is derived as Eq. (4.5) which is shown in Fig. 4.5 as follows:

$$q_{cr,sub} = q_{cr,sat}^* \left(1 + K_3 \Delta T_{sub}^{0.73} \right) \quad (4.5)$$

where, Eq. (4.5) is the value of CHF resulting from the HSN at atmospheric pressure under saturated condition. The values K_3 and $q_{cr,sat}^*$ are 0.16 and 0.75×10^6 , respectively, from this study.

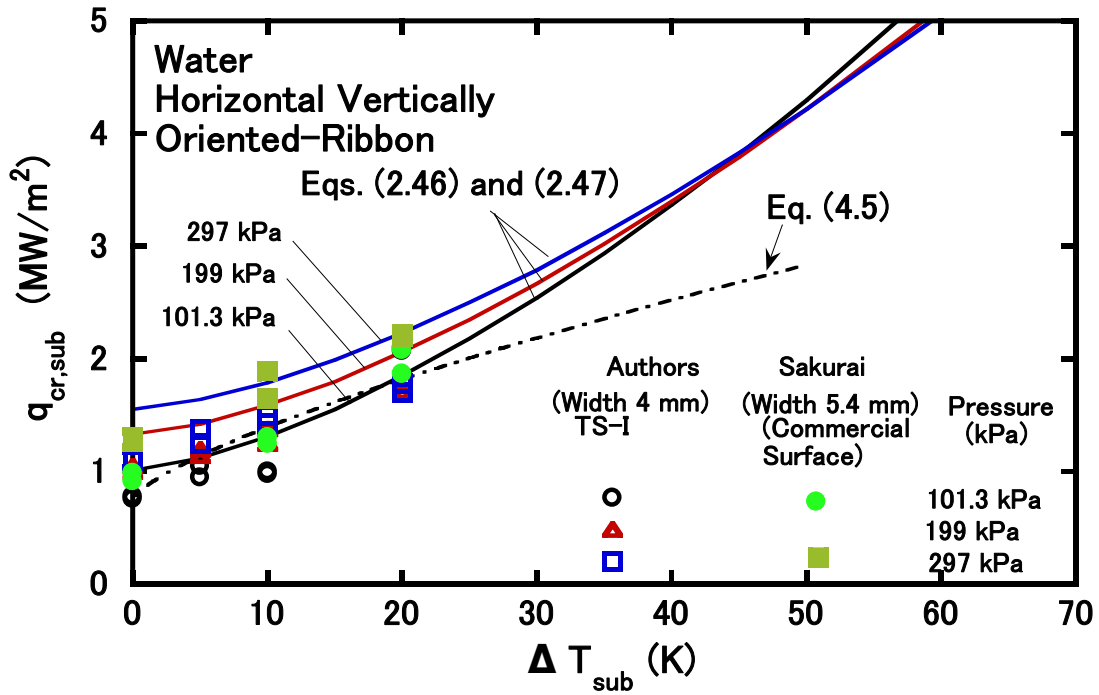


Fig. 4.5 The steady-state CHF versus liquid subcooling with pressures as a parameter

Figure 4.6 shows the steady-state CHFs on horizontal vertically oriented ribbon heater (TS-I only) in a pool of water due to quasi-steadily heat inputs at period, τ , 20 s, for pressures with subcooling as a parameter. The measured CHFs are plotted with the experimental CHF [16] and the corresponding data according to the Eqs. (2.46) and (2.47). It can be seen that the measured data in this study for various pressures are independent of subcooling.

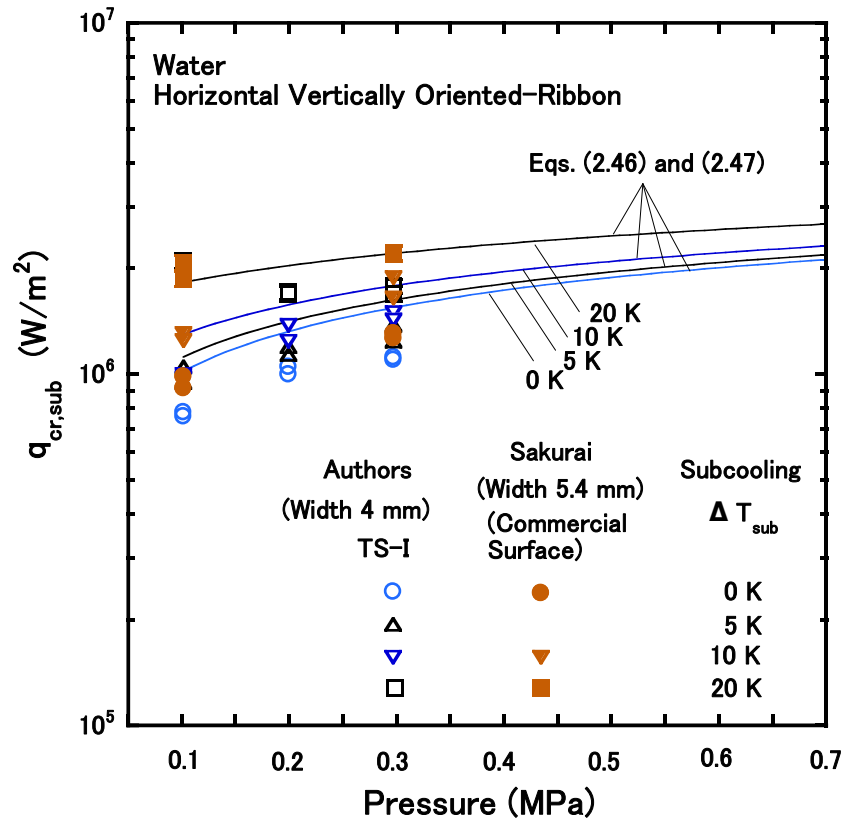


Fig. 4.6 The steady-state CHF versus pressure with liquid subcoolings as a parameter

4.7 Typical heat transfer processes for transient CHF

The typical heat transfer processes of transient CHF for long, short and intermediate periods, respectively, measured on horizontal vertically oriented ribbon heater with TS-I in a pool of water at 199 kPa under subcooling of 20 K are shown in Fig. 4.7. They are taken at the periods, τ , of 10 s, 55 ms and 5 ms, respectively. The heat transfer process due to period, τ , of 10 s increases from natural convection regime. Then, the boiling initiation occurs at the point A, where the surface superheat is 35 K. After boiling initiation, the surface superheat slightly decreases to the point B due to activation of cavities. As there are various sizes of cavities on heated surface, it is assumed that nucleate boiling at point B comes from large cavities. With the increase of heat flux, numerous cavities come to activations. As the heat flux increases with an increase of

surface superheat as shown in Fig. 4.7, the latter activated cavities might be small cavities.

Then, the heat flux increases up to CHF at the point C, through fully developed nucleated boiling (FDNB) regime which is plotted by dotted line using Rohsenow's correlation. The heat transfer process due to period, τ , of 5 ms increases from non-boiling regime to film boiling with a nucleate boiling for a while. The initiation of boiling commences on the conduction regime on the point A' at the surface superheat of 54 K. Then, the heat flux and surface superheat slightly increase up to CHF at the point C'. The heat transfer process due to period, τ , of 55 ms increases from transient conduction regime. The initiation of boiling begins on conduction regime on the point A'' at surface superheat of 43 K. After boiling initiation, the surface superheat first increases, then decreases and again increases with an increase of heat flux. The CHF on point C'' is reached with insufficient developed nucleate boiling.

Moreover, the heat fluxes at boiling initiation, q_i , and the CHFs are shown by solid circles and square marks, respectively. The heat fluxes at boiling initiation, q_i , can be plotted in a single line using broken line, namely, the incipient heat flux curve. The CHFs can be seen at the three places such as around C at the FDNB curve, around C' situated a slight beyond the incipient heat flux curve, q_i curve, and around C'' at the place between the two curves. They can be named as the first, second and third groups of CHFs.

Figure 4.8 shows the heat transfer processes due to exponential heat inputs at the periods, τ , of 5 s and 7 s which were measured on horizontal vertically oriented ribbon heater with CS, TS-I and TS-II, respectively, in a pool of water at 101.3 kPa under saturated condition. The order of surface superheats of boiling initiation are 10 K, 19 K and 27 K for the TS-II, CS and TS-I, respectively. Accordingly, the TS-II contributes the better heat transfer enhancement in FDNB regime compare to those of the CS and TS-I, in contrast, the TS-I has the lowest heat transfer rate in this study. It is assumed that the better heat transfer rate leads to the higher CHF. Consequently, the CHFs of the TS-II, CS and TS-I are resulted at 1.03, 0.87 and 0.75 MW/m² at surface superheats of 19 K, 23 K and 30 K, respectively. The heat transfer processes were evaluated with Rohsenow's correlation.

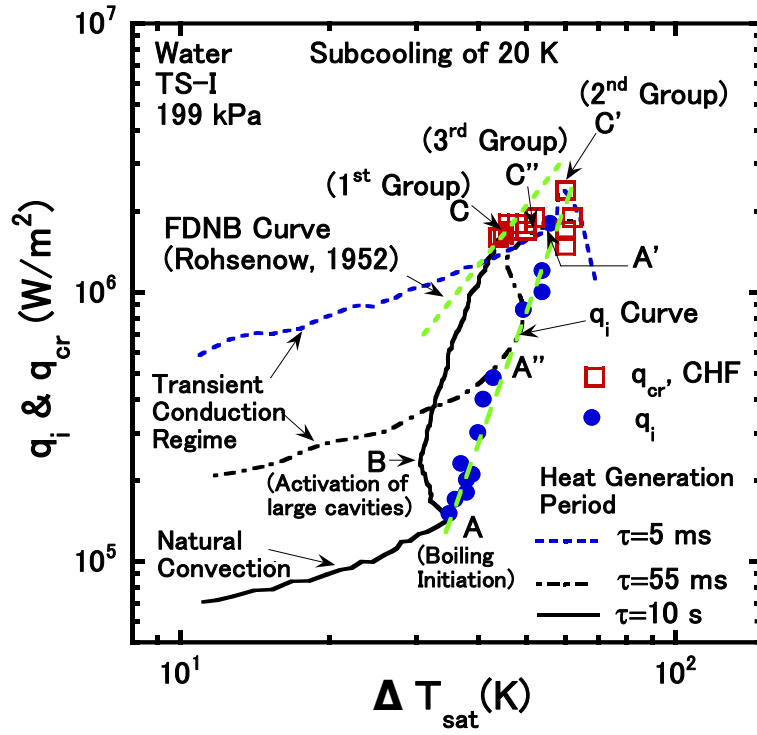


Fig. 4.7 Typical heat transfer processes and the three groups of CHF for TS-I

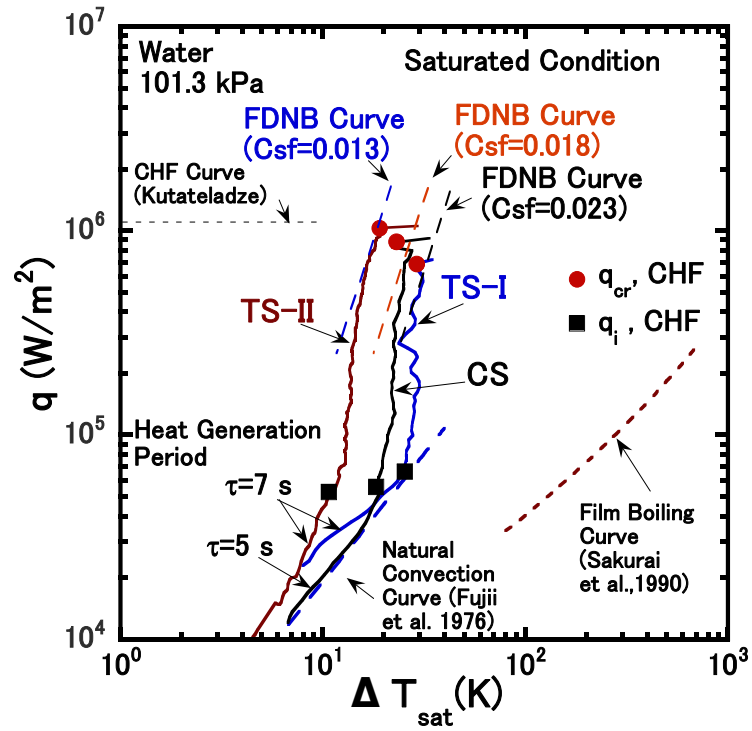


Fig. 4.8 Typical heat transfer processes due to quasi-steadily heat inputs for CS, TS-I and TS-II

The values of the liquid-solid combination, C_{sf} , for water-platinum in Rohsenow equation was taken as 0.013 and the exponent, n , of Prandtl number for water was 1.0. As shown in Fig. 4.8, the heat transfer process of the TS-II in this study compromises Rohsenow's correlation with $C_{sf}=0.013$. However, $C_{sf}=0.018$ and 0.023 are found in heat transfer processes of the CS and TS-I, respectively.

The effect of the surface roughness and contact angle on the transient CHF based on the boiling mechanism will be explained as follows. The transient CHF depends on surface superheat at boiling initiation, ΔT_i . The ΔT_i is influenced by the nucleation mechanism at boiling initiation. Nucleation originates from trapped vapor of active cavities as well as untrapped vapor in flooded cavities. Therefore, the TS-I in this study having very fine surface was prepared to verify the effect of pre-pressurization (or) flooded cavities. As the ΔT_i of TS-I is similar to the result of the TS-II with pre-pressurization up to 4.4 MPa acquired by [63], the TS-I has demonstrated to be a characteristic of flooded cavities which is a satisfactory to the two models suggested by [16] and [15]. However, the contact angle, θ , is important to nucleation primarily and, on the other hand, cavity angle, β , shapes nucleation surface superheat [10]. As the cavity angle, β , is difficult to measure, it is interesting how to determine β and its effect.

In order to clarify the mechanism of nucleation and superheating concerning with the test heaters of the CS, TS-I and TS-II as shown in Fig.4.7 and 4.8, a model for lower limit of HSN temperature in which nucleation originates from flooded cavities suggested in [16] was firstly evaluated. The predicted result revealed that an increase of ΔT_i corresponded to a decrease of the θ . Moreover, it shows that the values of the ΔT_i between the contact angle of 50~60° compromise to about 200 K. This result indicates a higher value for corresponding surface superheat obtained for CS, TS-I and TS-II as shown in Fig.4.7 and 4.8.

Again, the ΔT_i depending on the contact angle, θ on the effect of cavity angle, β , are performed using the nucleation and superheating model in which it is assumed no vapor in cavities [15]. However, in this model, the prediction of ΔT_i concerned not only the contact angle, θ , and cavity angle, β , but also equilibrium bubble radius, (or) nucleation radius, r_k . The r_k which corresponds to $\Delta T_i=169$ K and 26 K at the system pressure of 199 kPa are 1 μm and 10 μm , respectively, [15]. To compare the values of the ΔT_i of the TS-I as shown in Fig. 4.7 with the corresponding value attained by this model, the r_k of

the TS-I is taken to be $1\ \mu\text{m}$ because TS-I possesses a very fine roughness. The predicted values of the ΔT_i at $\theta=60^\circ$ for β ranging from 0 to 100° varies from 25 K to 130 K. The experimental ΔT_i of the TS-I for subcooling of 20 K at 101.3 kPa in water is varying from 35 K ~ 54 K. It means the experimental result agrees to corresponding data between β ranging from 0 and 50° .

In case of TS-II, the critical nucleation radius was assumed to be larger than $1\ \mu\text{m}$ because the surface roughness of TS-II is over five times larger than TS-I and pre-pressurization has not been carried out to the TS-II as shown in Fig.4.8. The larger nucleation radius of TS-II generates the small surface superheat at boiling initiation. Alternatively, it has potential to increase the CHF. Based on the explained nucleation mechanism, the ΔT_i corresponds on the order of TS-II<CS<TS-I, respectively. On the other hand, the CHF increases on the order of TS-II>CS>TS-I, respectively.

4.8 Transient CHF under saturated condition

Figure 4.9 shows the transient CHF, q_{cr} , versus the periods, τ , that were measured at atmospheric pressure under saturated condition for CS, TS-I and TS-II. The period, τ , was ranged from 5 ms to 20 s. The transient CHF, q_{cr} , of the CS and TS-I are in line with the typical trend [16] as follows: at first, it slightly increase up to maximum CHF from a steady-state CHF, then q_{cr} significantly decreases down to minimum CHF and finally q_{cr} increases again with a decrease in period. The three groups of CHFs, namely, the first, second and third groups can be seen clearly.

The first group of CHFs was resulted from the heat transfer process corresponding to the period of 10 s as seen in Fig. 4.7. The first groups of CHFs were mainly observed at periods higher than 100 ms for the CS and TS-I, on the other hand, periods higher than 50 ms for the TS-II. Moreover, the first group of CHFs for period measured on the TS-II gives a higher value of about 16% than the CS and 28 % than the TS-I. It was occurred that the CHFs for period for the conditions of the without and with pre-pressurization up to 2.0 MPa, respectively, measured on the TS-II has the same value.

The first groups of CHFs were tested with the previous corresponding values based on hydrodynamic instability model which were plotted with solid lines. The corresponding

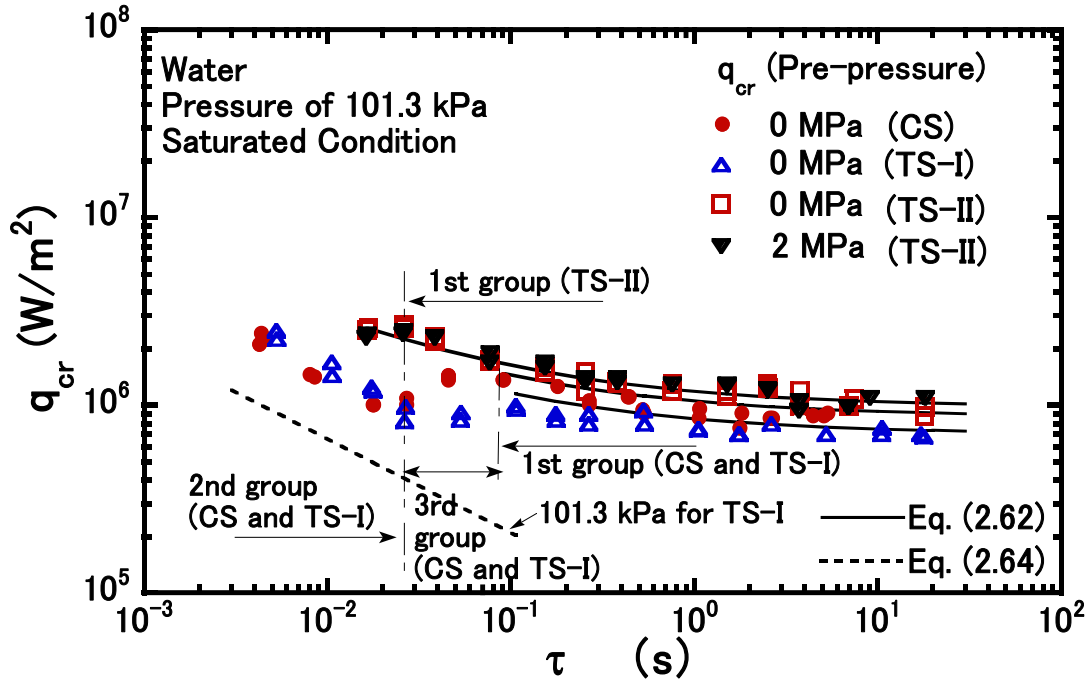


Fig. 4.9 The relation of q_{cr} and τ for saturated condition at 101.3 kPa for CS, TS-I and TS-II

values were derived from Eq. (2.62) according to the [16] in which $q_{cst,sub}$ is taken from the respective measured steady-state CHF for pressure and subcooled condition in this study.

Figure 4.10 shows the transient CHF, q_{cr} , versus the periods, τ , that were measured at pressures under saturated condition on TS-I. The increasing trends of the first groups of CHF for periods at pressures are similar and they increase depending on pressure. The first groups were predominantly occurred at periods higher than 100 ms for 101.3 kPa and 200 ms for 199 and 297 kPa, respectively.

The second group of CHF was occurred for the periods shorter than the periods corresponding to minimum CHF as seen in Figs.4.9 and 4.10. The second groups of CHF attained only for CS and TS-I were induced by heat transfer process which corresponds to typical heat transfer process caused by period of 5 ms as presented in Fig. 4.7. The trends of second groups of CHF increase asymptotically. They were evaluated by the CHF data described by Eq. (2.64) which compromise with the heat flux at boiling initiation in transient CHF (Sakurai and Shiotsu, 1977). It is based on the conduction heat

transfer coefficient, h_c , for exponential heat input, experimental surface superheat of boiling initiation due to HSN in conduction regime, ΔT_i , and the liquid subcooling, ΔT_{sub} . The h_c in Eq. (2.65) has equivalent function of $(k_l \rho_l c_{pl} / \tau)^{1/2}$ at the condition of $(t/\tau \geq 3)$ (Hayashi et al., 1963). As seen in Figs. 4.9 and 4.10, the correlation is lower than the measured result. It is due to the two facts that the occurrence of the nucleation at boiling initiation for a while can cause the decreasing of the surface superheat at boiling initiation and increasing the critical heat flux.

The third group of CHF is found on the region from the maximum CHF of the first group down to the minimum one of the second group. The third group of CHFs was induced by the heat transfer process which corresponds to typical heat transfer process due to the period of 55 ms as seen in Fig. 4.7. The third groups of CHFs for periods exist only for experiment results of CS and TS-I under atmospheric and saturated condition as indicated in Fig. 4.9. Moreover, the third group of CHF is occurred at pressures for TS-I as seen in Fig. 4.10. In Fig. 4.9, the third group resulting from the TS-I is lower than the CS, though they can be observed in the same interval of period.

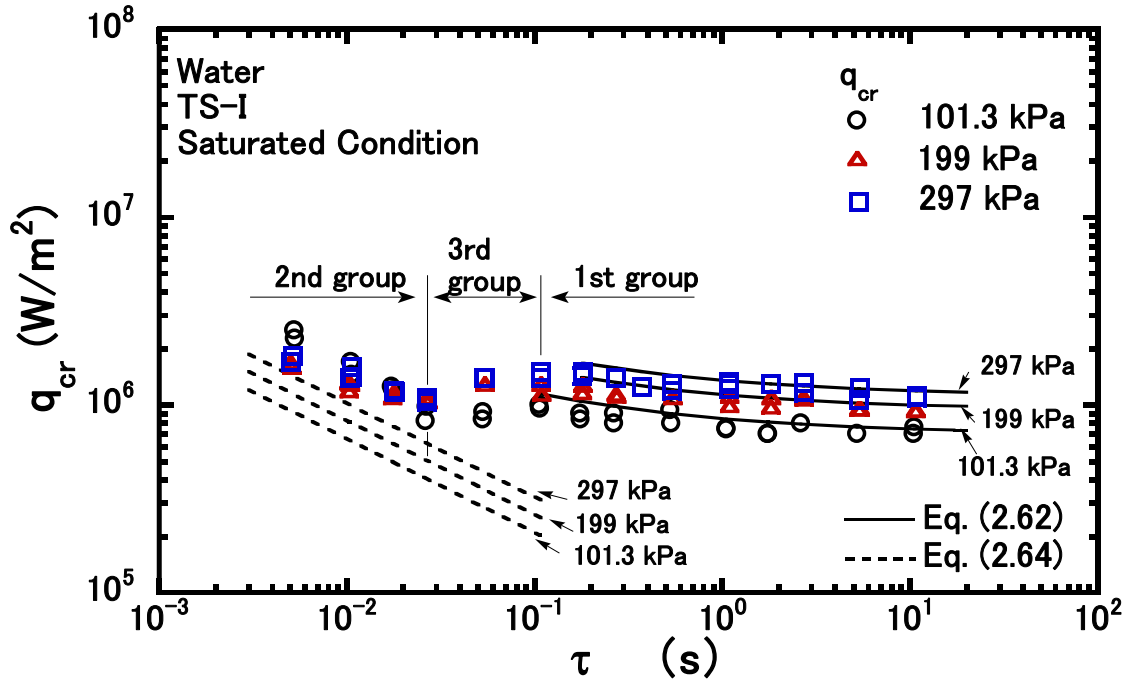


Fig.4.10 The relation of q_{cr} and τ for saturated condition at pressures for TS-I

4.9 Transient CHF under subcooled condition

Transient CHF, q_{cr} , versus the periods, τ , ranging from 5 ms to 10 s under subcooling of 20 K at pressures measured on TS-I is shown in Fig.4.11. The typical three groups of CHF are perceived obviously. The increasing trends of the first groups of CHF for periods up to maximum CHF at pressures under subcooled condition are slightly lower than the corresponding results obtained on saturated condition. The reason is that the heat fluxes which belong to the maximum CHF at the first group under subcooled condition reached their CHF early due to the rapid increase of surface superheat and degraded nucleate boiling. Moreover, the first groups of CHF decrease with the increase of pressure. The measured quasi-steady-state CHF are compared with the corresponding values of Eq. (2.62). It was occurred that the maximum CHF of the first groups at pressures are lower than the corresponding values. The second group of CHF on 101.3 kPa under subcooling of 20 K was observed at the shorter period. The trends of second groups of CHF induced on 199 kPa and 297 kPa under subcooling of 20 K are longer than that of 101.3 kPa under subcooling of 20 K. The third groups of CHF on 199 and 297 kPa under subcooling of 20 K are shorter than 101.3 kPa under subcooling of 20 K.

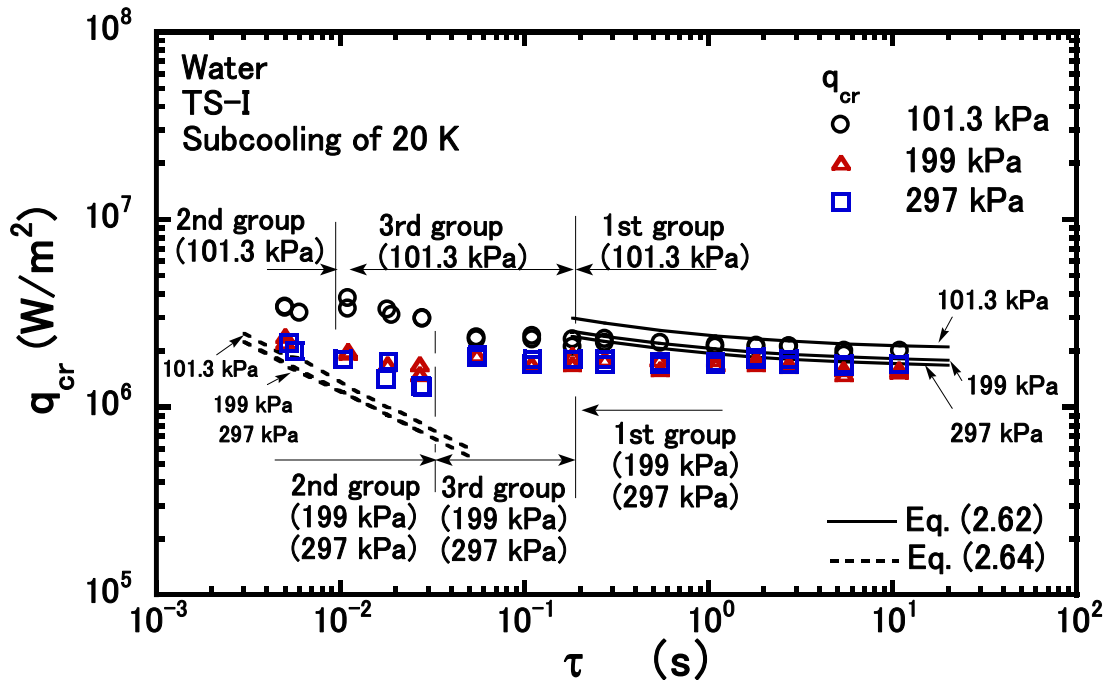


Fig. 4.11 The relation of q_{cr} and τ for subcooling at pressures for TS-I

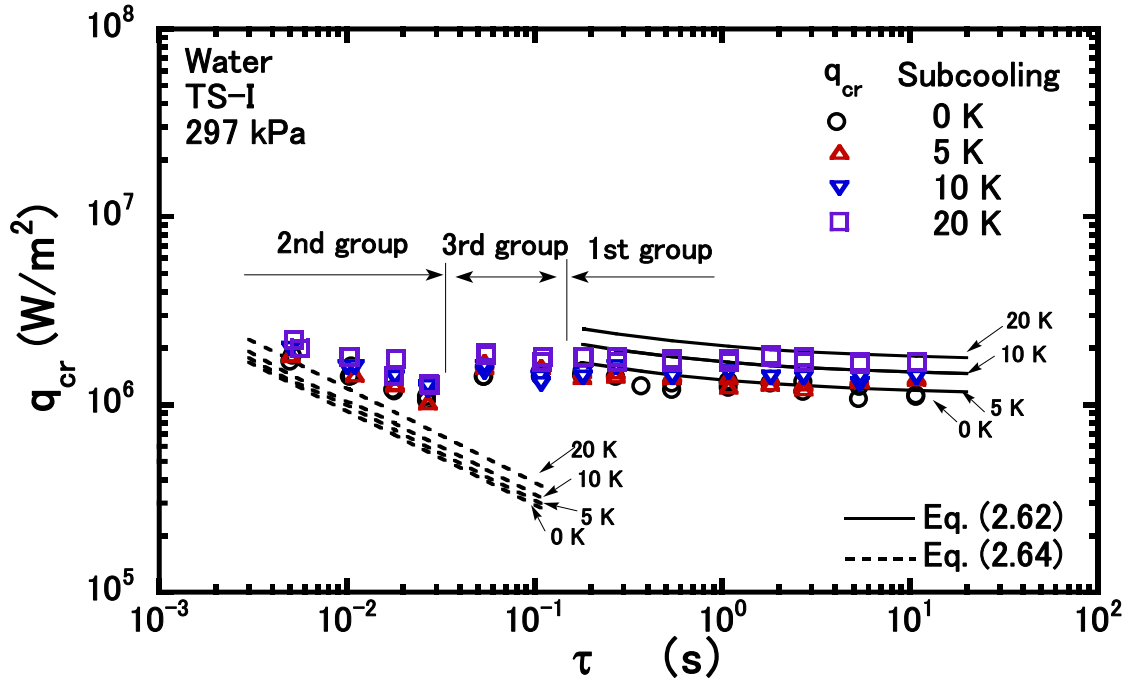


Fig. 4.12 The relation of q_{cr} and τ for subcooling at 297 kPa for TS-I

Figure 4.12 shows transient CHF, q_{cr} , versus the periods, τ , ranging from 5 ms to 10 s at 297 kPa under different subcoolings from 0 to 20 K that were measured on TS-I. The increasing trends of the first groups of CHF for periods at 297 kPa under different subcoolings are depending on subcooling. At the first group of CHF, the experimental results are satisfied with the corresponding values at periods higher than 500 ms. The maximum CHF of the first groups at subcoolings are lower than corresponding values. The typical trends of the second and third groups of CHF which increase with the increase of subcooling are also observed at 297 kPa under subcoolings. However, the second groups of CHF for periods have the elevated values over the correlation.

4.10 Effect of contact angle on surface orientation

The steady state CHF analysis on the effect of contact angle obtained on horizontal vertically oriented ribbon heaters at atmospheric pressure under saturated condition in pool of water for TS-I, TS-II and CS is demonstrated in Fig.4.13. The CHF are due to quasi-steadily heat inputs at the period, τ , of 5 s for CS and 7 s for TS-I and TS-II,

respectively. The measured CHF values for contact angle, θ , give rise to higher values with the decrease of contact angle. The measured CHF values were evaluated and plotted with the corresponding values [64] which are based on the combination of Zuber's correlation and the functions of contact angle, θ , and surface orientation, ϕ . In this figure, the blue solid line represents the surface orientation of 90° , the black broken line represents surface orientation of 45° and the red dotted line represents upward orientation of 0° . The correlation is postulated that the decrease of contact angle has the higher CHF value, on the other hand, the higher value of orientation has the decline of CHF. However, the experimental results of the CS, TS-I and TS-II in this study provide elevated values over the corresponding ones.

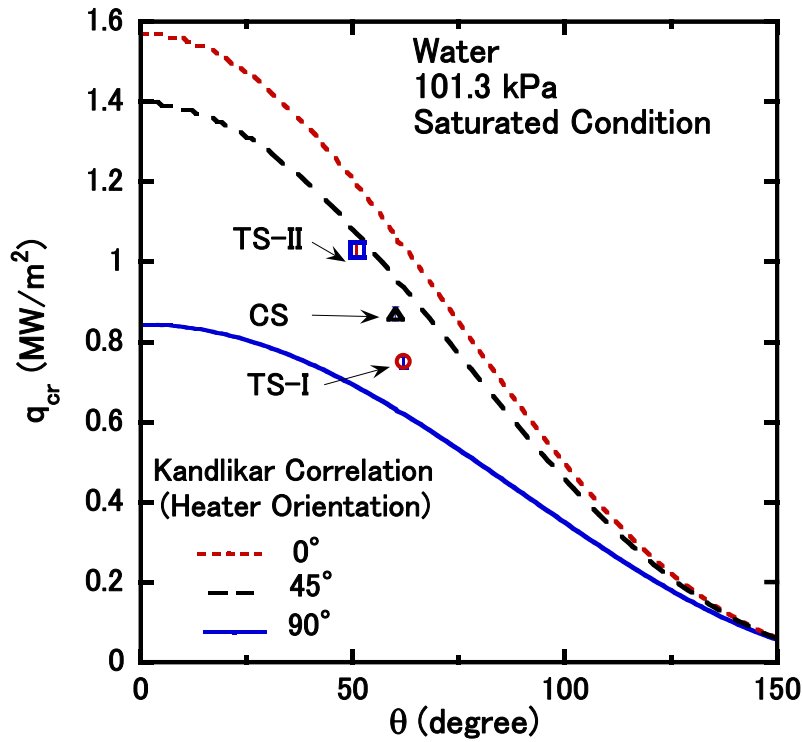


Fig. 4.13 The effects of contact angle, θ , on CHF obtained on horizontal vertically oriented ribbon heaters due to exponential heat inputs at steady state condition at atmospheric pressure under saturated condition in pool of water for CS, TS-I and TS-II

4.11 Vapor behavior due to exponential increasing heat inputs on horizontal vertically oriented ribbon for TS-I

Figure 4.14 shows heat transfer processes due to exponential increasing heat inputs with periods of 20 s and 50 ms, respectively, on horizontal vertically oriented ribbon with TS-I in saturated water at atmospheric pressure.

The non-boiling regime of heat transfer processes due to exponential period of 20 s comes from natural convection. The points (a) to (e) on heat transfer process due to period of 20 s are boiling initiation to critical heat flux, respectively. The corresponding vapor behaviors are shown in Fig. 4.15 where (a) in Fig. 4.15 represents boiling initiation, (c) in Fig. 4.15 represents isolated nucleate boiling, (d) in Fig. 4.15 indicates vapor column

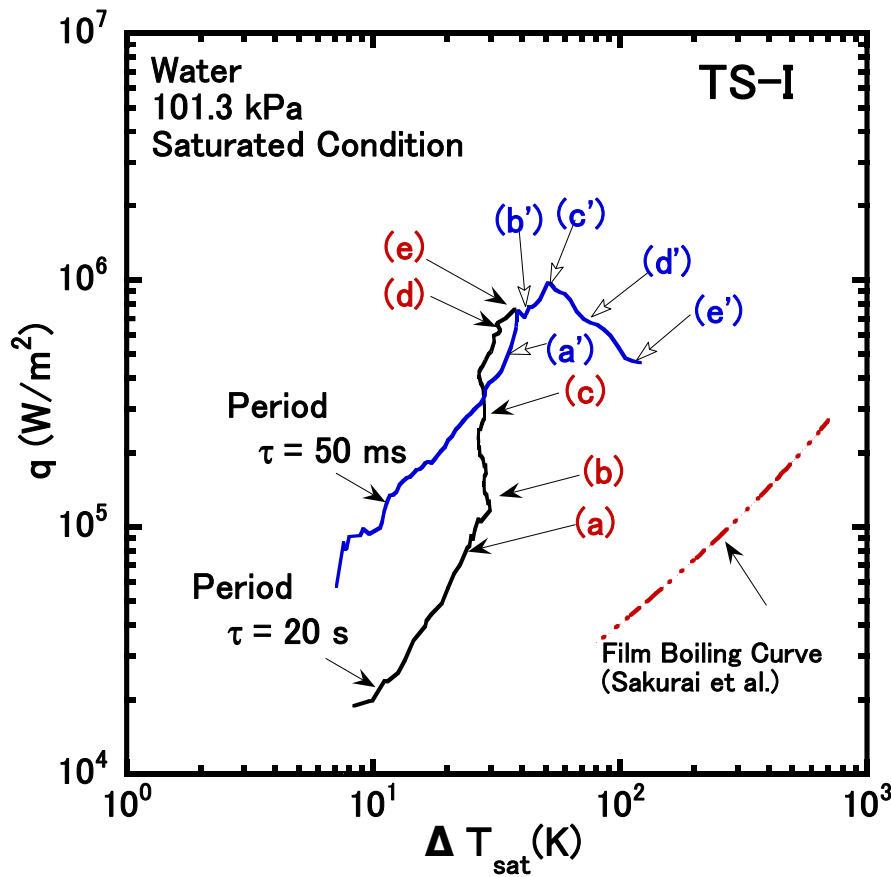


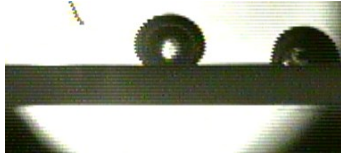
Fig. 4.14 Heat transfer heat transfer processes due to exponential increasing heat inputs with periods of 20 s and 50 ms, respectively, on horizontal vertically oriented ribbon with TS-I in saturated water at atmospheric pressure



(a) $t=0$ s



(d) $t=21.60$ s



(b) $t=5.00$ s



(e) $t=24.12$ s



(c) $t=13.68$ s

Fig. 4.15 Vapor behavior due to exponential increasing heat inputs with periods of 20 s on horizontal vertically oriented ribbon with TS-I in saturated water at atmospheric pressure

in fully developed nucleate boiling and (e) in Fig. 4.15 represents the vapor behavior of critical heat flux at fully developed nucleate boiling. Vapor behavior in the (c) and (d) in Fig. 4.15 shows less nucleation sites on the heater. The larger number of nucleation sites are seen in (e) in Fig. 4.15. It takes about 24 s to reach critical heat from boiling initiation.

The points (a') to (e') in Fig. 4.14 on heat transfer process due to period of 50 ms are boiling initiation to critical heat flux, respectively. The corresponding vapor behaviors are shown in Fig. 4.16 where (a') in Fig. 4.16 represents boiling initiation, (c') in Fig. 4.16 represents critical heat flux, (d') and (e') in Fig. 4.16 are the vapor behavior in the transition regime, respectively. It takes 16 ms to reach critical heat flux from boiling

initiation. The vapor behaviors from boiling initiation to critical heat flux do not reveal fully developed nucleate boiling as shown in Fig. 4.16. After boiling initiation, the number of nucleation sites become larger rapidly as seen in (b') of Fig. 4.16 which is 8 ms after boiling initiation and as indicated in (c') of Fig. 4.16 which is 16 ms from boiling initiation. The vapor behaviors in Fig. 4.16 are named as heterogeneous spontaneous nucleation on horizontal vertically oriented ribbon with TS-I. Thus, the mechanism of critical heat flux due to exponential heat input with period of 50 ms is suggested to be due to heterogeneous spontaneous nucleation.

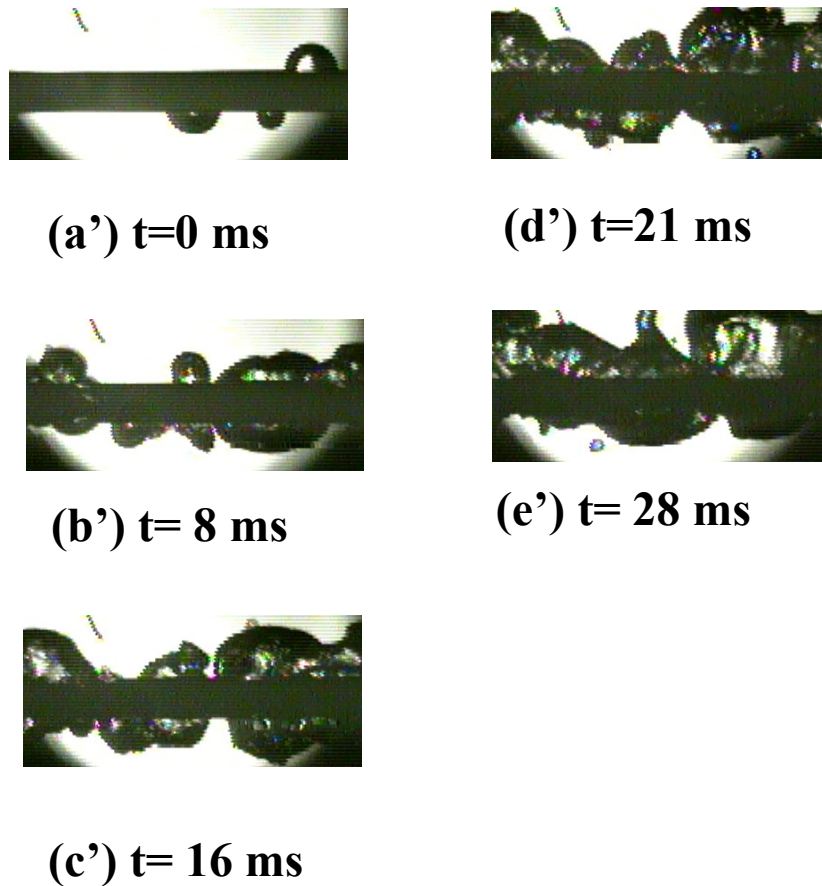


Fig. 4.16 Vapor behavior due to exponential increasing heat inputs with periods of 50 ms on horizontal vertically oriented ribbon with TS-I in saturated water at atmospheric pressure

4.12 Summary

The steady and transient CHF caused by exponentially increasing heat inputs on horizontal vertically oriented ribbon in water have been carried out. The Commercial surface (CS), treated surface I (TS-I) and treated surface II (TS-II) ribbon heaters were utilized. For CS and TS-II, the experiments were done under saturated condition at 101.3 kPa. However, for TS-I, the experiments were completed under subcooling of 0 K to 20 K at 101.3 kPa to 297 kPa.

- (1) The non-boiling heat transfer compromises with the existing equations according to the experimental results of the TS-I. However, the measured steady-state CHF of the TS-I have lower value of CHF compare to the existing experimental steady-state CHF and the corresponding values.
- (2) In this study, the TS-II enhances CHF about 16 % and 28 % compare to the CS and the TS-I at the first group of the transient CHF, q_{cr} .
- (3) The transient CHF, q_{cr} on periods obtained at saturated condition are depending on pressures. On contrary, they are independent of pressure at subcooling of 20 K according to the results of the TS-I.
- (4) The first groups of CHF's agree with the corresponding equation. However, the second groups of CHF's have elevated values compare to the corresponding values.
- (5) The steady-state CHF's of the CS, TS-I and TS-II in this study are observed at the higher values than the correlation on the effect of contact angle and surface orientation.

Chapter 5

Effects of Pre-pressurization on Transient Boiling Heat Transfer and Critical Heat Flux on Different Surfaces under Atmospheric Conditions

5.1 Experimental conditions

The experimental conditions for CS, TS-I and TS-II to perform transient CHF due to exponential increasing heat inputs on the effect of pre-pressurization in this study are described in Table 5.1.

Table 5.1 Experimental conditions of transient CHF due to exponential increasing heat inputs on the effect of pre-pressurization

Parameter	CS	TS-I	TS-II
Liquid	Water	Water	Water
Q (Heat Input)	$Q_0 \exp(t/\tau)$	$Q_0 \exp(t/\tau)$	$Q_0 \exp(t/\tau)$
P (System Pressure)	101.3 kPa	101.3 kPa	101.3 kPa
ΔT_{sub} (Subcooling)	0 K	0 K	0 K
τ (Period)	5 ms ~ 5 s	5 ms ~ 20 s	7 ms ~ 20 s
Pressurization	0 MPa	0 MPa	0/4.4 MPa
Material	Platinum	Platinum	Platinum
L (length)	30 mm	30 mm	41 mm
W (Width)	4 mm	4 mm	4 mm
$2 \times \delta$ (Thickness)	0.1 mm	0.1 mm	0.2 mm
R_a	$0.12 \pm 0.015 \mu\text{m}$	$0.04 \pm 0.005 \mu\text{m}$	$0.22 \pm 0.02 \mu\text{m}$
θ	$60.6 \pm 1.3^\circ$	$62.0 \pm 1.0^\circ$	$51.5 \pm 0.7^\circ$

5.2 Effect of pre-pressurization to surface superheat at boiling initiation

The results of surface superheat at boiling initiation, ΔT_i , due to quasi-steadily increasing heat inputs versus pre-pressurization are shown in Fig.5.1. Pre-pressurization up to 4.4 MPa before each experimental run was carried out on horizontal vertically oriented ribbon heater with the TS-II having R_a value of $0.22 \pm 0.02 \mu\text{m}$ and θ value of $51.5 \pm 0.7^\circ$ in water under saturated condition at atmospheric pressure. The pre-pressurization can change active cavities to flooded cavities. In this experiment, the ΔT_i due to quasi-steadily increasing heat inputs and inducing of heterogeneous spontaneous nucleate boiling were investigated. The two demonstrated straight lines based on the measured results revealed that they have different mechanisms at boiling initiation. The line represented for the increasing ΔT_i value up to pre-pressurization of 0.88 MPa is suggested to be due to nucleation sites on the surface of ribbon heater. On the contrary, the ΔT_i values which are approximately constant for pre-pressurization from 0.88 to 4.4 MPa are assumed to be due to HSN. The limit of ΔT_i which is about 40 K due to HSN on horizontal cylinder for quasi-steadily increasing heat input in pool of water by pre-pressurization up to 5 MPa have been reported by Sakurai [16]. As the ΔT_i due to HSN depends on surface condition, the value of ΔT_i due to HSN in this study by pre-pressurization up to 4.4 MPa to the TS-II is lower than the ΔT_i due to HSN attained on commercially available horizontal cylinder.

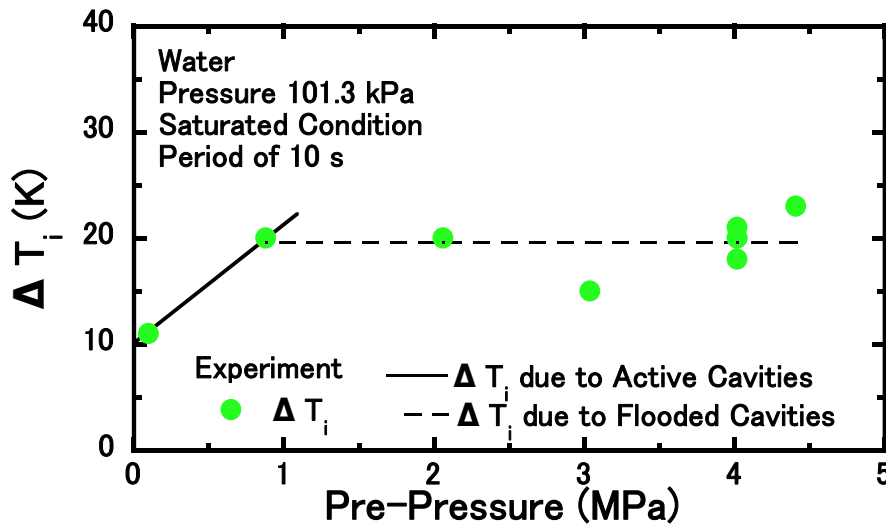


Fig. 5.1 Surface superheat at boiling initiation vs. pre-pressurization

5.3 Effect of pre-pressurization to time dependence of surface temperature, heat flux and heat generation rate

The time dependence of surface temperature, T_s , heat flux, q , and Heat Generation Rate, Q , versus pre-pressurization is shown in Fig. 5.2. They were performed due to exponential heat input for the period, τ , of 500 ms on TS-II (4.4 MPa) in a pool of boiling water at 101.3 kPa. The heat generation rate, Q , increases exponentially for the whole process. However, T_s and incipient heat flux, q_i , increase along heat generation curve up to overshoot temperature at boiling initiation, T_{ov} , and q_i , respectively. Then, they decrease rapidly and again increase gradually up to the CHF point. It is suggested that the phenomena such as T_{ov} and delayed q_i are due to the pre-pressurization up to 4.4 MPa which is able to flood the test heater.

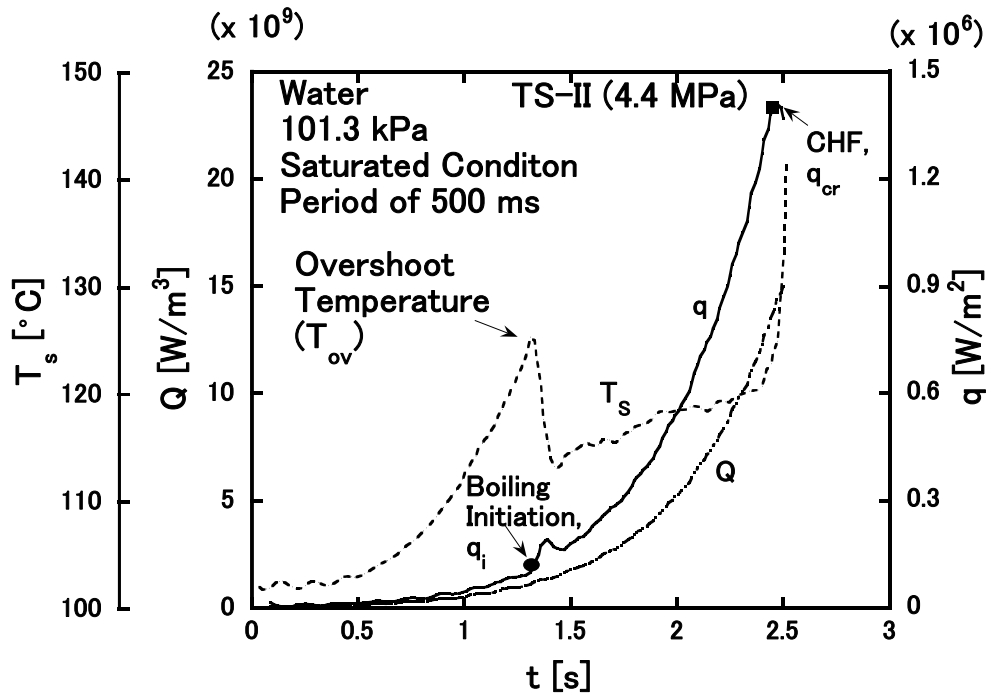


Fig. 5.2 Time dependence of heat generation rate, surface temperature and heat flux for TS-II (4.4 MPa)

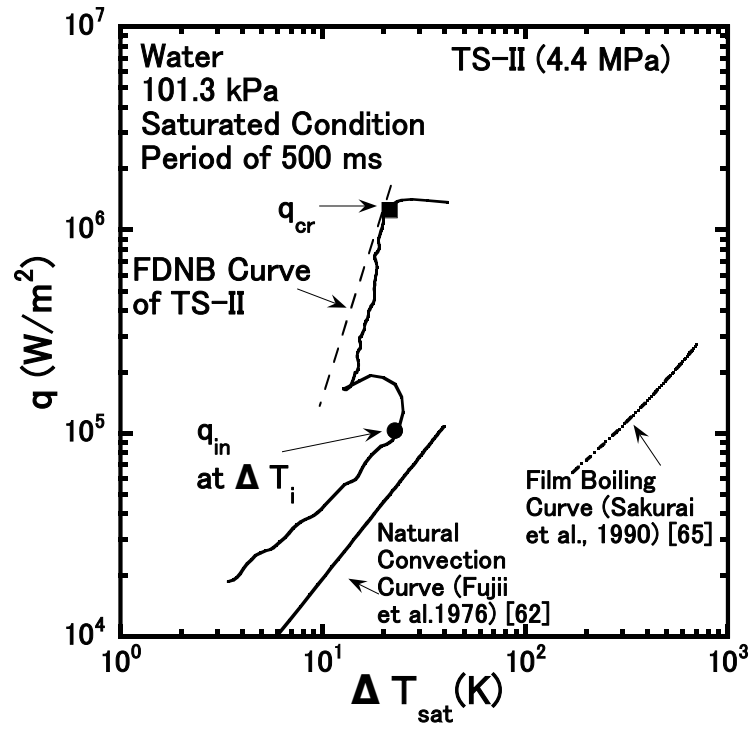


Fig.5.3 The heat transfer process for TS-II (4.4 MPa) which is depicted in Fig.5.2

The heat transfer process, q , in Fig. 5.2 is depicted in Fig.5.3 as the function of surface superheat, $\Delta T_{\text{sat}} = T_s - T_{\text{sat}}$. The T_{sat} is saturated temperature of liquid. In this figure, the heat transfer process increases from natural convection to film boiling through fully developed nucleate boiling (FDNB). Decreasing of ΔT_{sat} after boiling initiation, ΔT_i , is due to activation of flooded cavities. The natural convection curve [62], fully developed nucleation curve [22] and steady-state film boiling curve [65] are illustrated for comparison.

5.4 Physical mechanism of boiling heat transfer due to pre-pressurization and exponential increasing heat inputs

The heat flux, q , is characterized by the relation of heat transfer coefficient, h , and ΔT_{sat} as follow:

$$q = h\Delta T_{\text{sat}} \quad (5.1)$$

In boiling heat transfer, q is divided into two conditions such as non-boiling and nucleation condition. Consequently, h can be categorized as non-boiling heat transfer coefficient and nucleate heat transfer coefficient. Non-boiling heat transfer coefficients due to exponential increasing heat inputs governed by natural convection heat transfer, transient conduction heat transfer and combined natural convection and transient conduction heat transfer [54] play role the different physical mechanisms of CHF. Generally, the transient conduction at non-boiling condition due to exponential increasing heat inputs is a major potential model to outcome CHF at q_i . Moreover, it is assumed that dissipation of nucleation sites due to surface condition and pre-pressurization can change the transition of heat flux. It is important to know what factor influences the mechanistic model at non-boiling and nucleation condition which shapes the CHF.

The heat flux at boiling initiation, q_i , and nucleate boiling, q_{nb} , can be characterized in Eqs. (5.2) and (5.3) based on the Rohsenow equation of

$$q = \mu_l h_{lv} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{c_{pl} \Delta T_{sat}}{C_{sf} h_{lv} \text{Pr}_l^n} \right)^3 \quad [22] \text{ as follows:}$$

$$q_i = C_1 \Delta T_i^n \quad (5.2)$$

$$q_{nb} = C_2 \Delta T_{sat}^n \quad (5.3)$$

The subscripts i , nb , C_1 and C_2 mean boiling initiation, nucleate boiling, factors of q_i and q_{nb} , respectively. As the ΔT_{sat} in Eq. (5.1) is inserted into Eqs. (5.2) and (5.3), factors of heat fluxes in Eqs. (5.4) and (5.5) were obtained.

$$C_1^{1/n} = h / q_i^{(n-1)/n} \quad (5.4)$$

$$C_2^{1/n} = h / q_{nb}^{(n-1)/n} \quad (5.5)$$

As described in Eq. (2.32), Kutateladze's nucleate boiling equation is shortened to the relation of heat transfer coefficient, heat flux and coefficient of thermophysical properties with the function of pressure as follow,

$$\frac{h}{q^{0.7}} = C(P) \quad (5.6)$$

To convert $h/q^{(n-1)/n}$ to $h/q^{0.7}$, the value of n in Eq. (5.2) to Eq.(5.5) is equivalent to 3.3.

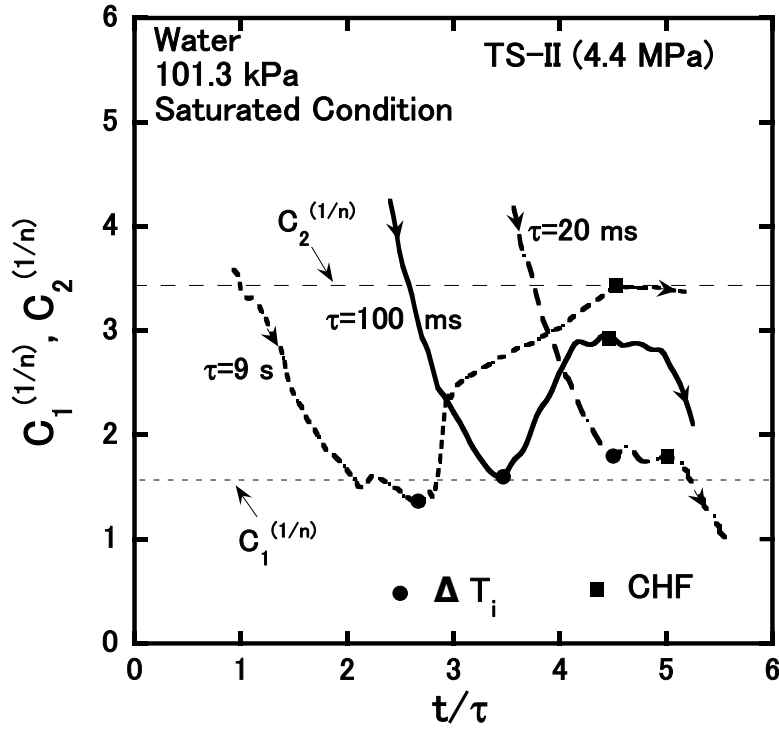


Fig. 5.4 Boiling heat transfer mechanism due to pre-pressurization and exponential increasing heat inputs

The factors of heat flux depending of time due to heat inputs for period, τ , of 9 s, 100 ms and 20 ms were illustrated with the function of non-dimensional period, (t/τ) in Fig.5.4. The higher increasing rate of heat input results from the shorter exponential period. It can be seen that the higher increasing rates of heat inputs have higher values of (t/τ) . All factors of heat fluxes descending from higher value down to lower one at boiling initiation terminates at the same line representing for $C_1^{1/n}$. On the contrary, at $(t/\tau) < 4$, heat transfer value increase again after boiling initiation. In this case, the lower value of (t/τ) resulting from exponential period, τ , of 9 s reaches to $C_2^{1/n}$. However, at $(t/\tau) > 4$, heat transfer value rapidly decreases after boiling initiation.

5.5 Typical heat transfer processes of transient CHF

Figure 5.5 illustrates the heat transfer processes due to quasi-steadily exponential heat input for CS (0 MPa), TS-I (0 MPa) and TS-II (0/4.4 MPa). The transition of the heat transfer processes increases from natural convection regime to film boiling through fully developed nucleated boiling (FDNB). The boiling initiation commences at natural convection regime.

The surface superheat at boiling initiations, ΔT_i , which is shown by solid circles are 9 K, 21 K and 23 K and 25 K with respect to the TS-II (0 MPa), CS (0 MPa), TS-II (4.4 MPa) and TS-I (0 MPa), respectively. It was occurred that the values of the ΔT_i depends on surface condition and the ΔT_i for the TS-I (0 MPa) is higher than the ΔT_i due to HSN obtained by TS-II (4.4 MPa) which is shown in Fig.5.5. For the TS-II (4.4 MPa), the surface superheat, ΔT_{sat} , decreases due to activation of flooded cavities after boiling initiation. In nucleate boiling regime, the heat transfer processes of the TS-II (0 MPa) and the TS-II (4.4 MPa) become identical regardless of the pre-pressurization. The TS-II (0/4.4 MPa) enhance the boiling heat transfer at the nucleate boiling regimes though the TS-I (0 MPa) reveals degradation of boiling heat transfer in this regime. As the surface superheat, ΔT_{sat} , at the nucleate boiling regimes for TS-II (0/4.4 MPa) decrease 7 K and 10 K, when compared with those of CS (0 MPa) and TS-I (0 MPa), respectively, it can be calculated by using the Eqs.(5.3) and (5.5) that the enhancement of the boiling heat transfer at the nucleate boiling regimes due to the TS-II (0/4.4 MPa) is $\sim 290\%$ and $\sim 430\%$ when compared with those of CS (0 MPa) and TS-I (0 MPa), respectively.

The heat transfer processes at the FDNB regimes for the TS-II (0/4.4 MPa), the CS (0 MPa) and TS-I (0MPa) were compared with Rohsenow's correlation [22]. The FDNB curves of the TS-II (0/4.4 MPa), the CS (0 MPa) and the TS-I (0 MPa) according to the Rosehnow's correlation are illustrated by broken lines in Fig. 5.5.

The values of the liquid-solid combination, C_{sf} , for water-platinum in Eq. (2.39) was taken as 0.013 and the exponent, n , of Prandtl number for water, Pr_l , was 1.7 [22]. The heat transfer process of the TS-II (0/4.4 MPa) in this study compromises the Rohsenow's correlation with $C_{sf}=0.013$. However, $C_{sf}=0.018$ and $C_{sf}=0.023$ are found at the heat transfer processes of the CS (0 MPa) and TS-I (0 MPa), respectively.

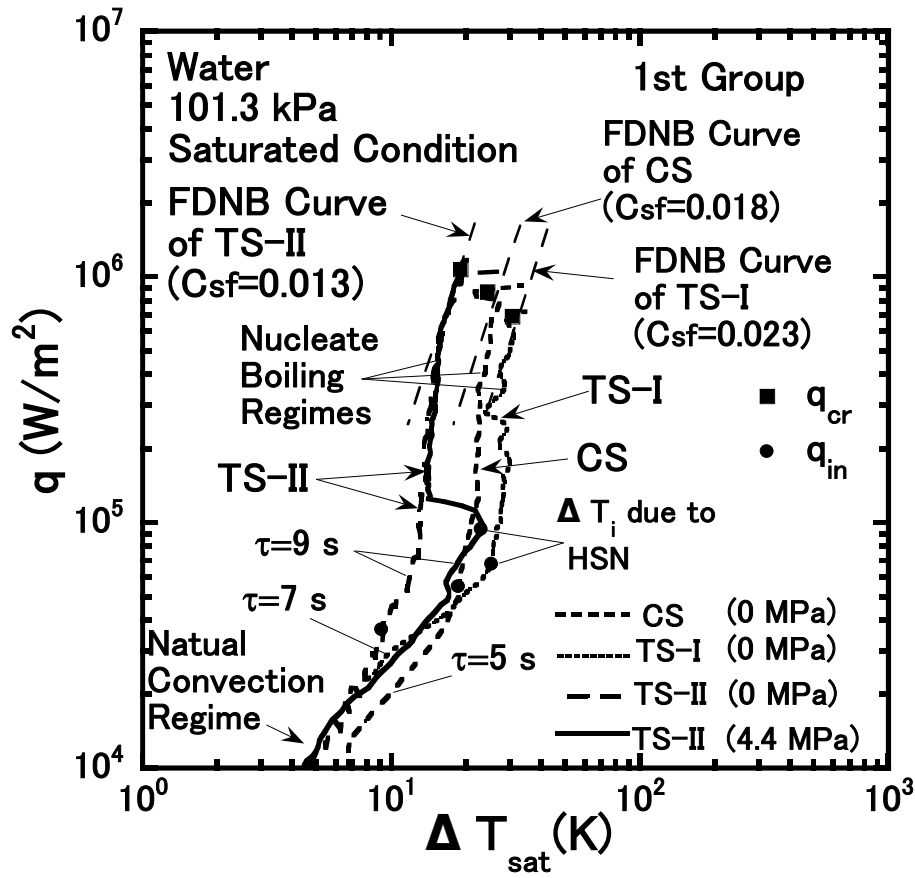


Fig.5.5 Typical heat transfer processes from natural convection to film boiling through FDNB

The values CHF for the TS-II (0/4.4 MPa), the CS (0 MPa) and the TS-I (0 MPa) are 1.14 MW/m², 0.95 MW/m² and 0.76 MW/m², respectively, which are depending on the surface condition. The better contribution of CHF due to the TS-II (0/4.4 MPa) would be due to enhanced surface condition, especially, having small contact angle of the TS-II could generate a higher rate of vapor departure. As is seen in the Fig.5.5, the surface superheat at the CHF for the TS-II (0/4.4 MPa) is lower than the ΔT_i due to HSN attained on TS-II (4.4 MPa). These kinds of heat transfer processes are generally found at the longer period or $\tau > 100$ ms though it is depending on the surface condition.

heat transfer and reach to the CHF in shortly. Moreover, it can be seen that the heat transfer process due to pre-pressurization of 4.4 MPa, TS-II (4.4 MPa), has the same transition with the TS-I (0 MPa) and the CS (0 MPa) from non-boiling to film boiling though the TS-II has the large surface roughness, R_a , and small contact angle, θ . After CHF, the heat transfer processes lead to film boiling regime with a degradation of heat transfer and increasing of surface superheats, ΔT_{sat} . These kinds of heat transfer processes are usually occurred at the short period or $\tau < 50$ ms.

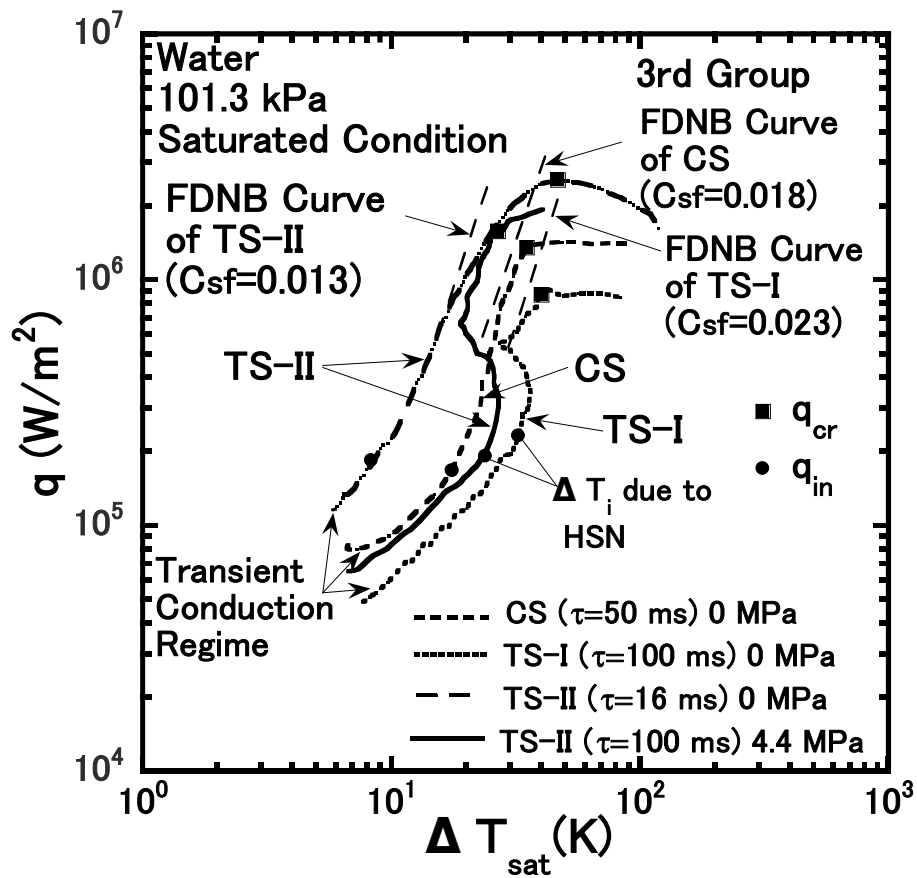


Fig. 5.7 Typical heat transfer processes from transient conduction to film boiling with insufficient FDNB

The heat transfer processes due to exponential period, τ , of 100 ms for TS-I (0 MPa) and TS-II (4.4 MPa), 50 ms for CS (0 MPa) and 16 ms for TS-II (0 MPa) are shown in Fig. 5.7. The heat transfer processes increase from transient conduction to film boiling

with insufficient FDNB. The boiling initiations begin on conduction regimes, respectively. The values of ΔT_i for the CS (0 MPa), the TS-I (0 MPa), the TS-II (0 MPa) and the TS-II (4.4 MPa) are found at 17 K, 33 K, 9 K and 24 K, respectively, depending on the surface condition. The ΔT_i for the TS-I (0 MPa) is higher than the ΔT_i due to HSN attained on the TS-II (4.4 MPa). After boiling initiations, the ΔT_{sat} of the q of the TS-I (0 MPa) and the TS-II (4.4 MPa) first increase, then decrease and again increase with the increases of the heat fluxes, respectively. The explosive boiling with simultaneous HSN at the boiling initiations of the TS-I (0 MPa) and the TS-II (4.4 MPa) can degrade the heat transfer and increase the ΔT_{sat} . Then, the rapid activations of the cavities due to HSN decrease the surface superheats. The heat transfer processes do not reach to the respective FDNB regimes which are demonstrated by the broken lines in Fig.5.7. In case of TS-II (0 MPa) for period, τ , of 16 ms, it has a better heat transfer and higher CHF because the ΔT_i is due to active cavities and it was not affected by HSN. The higher to lower value of the CHF on the surface condition is attained on the order of TS-II, CS and TS-I, respectively. Because the ΔT_{sat} at the CHF and the ΔT_i due to HSN are similar for the TS-II (4.4 MPa) and the TS-I (0 MPa) as is seen in Fig.5.7, it is assumed that the CHFs achieved on the TS-II (4.4 MPa) and the TS-I (0 MPa) are resulting from the HSN. These kinds of heat transfer processes can be mainly observed at the intermediate period or $50 \text{ ms} < \tau < 100 \text{ ms}$ for the CS (0 MPa), the TS-I (0 MPa) and the TS-II (4.4 MPa), respectively, and $16 \text{ ms} < \tau < 50 \text{ ms}$ for the TS-II (0 MPa).

5.6 Transient CHF for CS, TS-I and TS-II

Figure 5.8 shows the transient CHF, q_{cr} , versus the exponential periods, τ , that were measured at atmospheric pressure under saturated conditions for CS (0 MPa), TS-I (0 MPa) and TS-II (0/4.4 MPa). The value of τ is ranging from 5 ms to 20 s. The values of CHF, q_{cr} , for the CS (0 MPa), the TS-I (0 MPa) and the TS-II (4.4 MPa) are in line with the typical trend according to the [16]: at first, it slightly increases up to maximum CHF from a steady-state CHF, then decreases down to minimum CHF and finally increases again with a decrease in period.

The first group of CHF was resulted from the heat transfer processes as shown in Fig.5.5 and they were mainly observed at $\tau > 50 \text{ ms}$ for the TS-II (0 MPa), $\tau > 100 \text{ ms}$

for the CS (0 MPa) and the TS-II (4.4 MPa), and $\tau > 200$ ms for the TS-I (0 MPa), respectively. The CHF for period measured on the TS-II (0/4.4 MPa) have the same value at the first group of CHF. However, it would seem that the experimental results of the TS-II (0 MPa) for τ ranging from 20 s down to 16 ms meet to the first group of CHF as is seen in Fig.5.8. However, when the heat transfer process of the TS-II (0 MPa) due to period, τ , of 16 ms was confirmed, it increased from transient conduction to film boiling without reaching the FDNB as shown in Fig.5.7. On the contrary, the heat transfer process of the TS-II (0 MPa) due to the period, τ , of 100 ms reaches to film boiling through the FDNB. Having consideration to these facts, the CHF resulting from the heat transfer processes due to τ ranging from 20 s down to 50 ms are considered to be the first group of CHF. At the measured first group of CHF for period, the TS-II (0/4.4 MPa) contribute the higher CHF of about 1.2 times and 1.5 times when compared with the CS (0 MPa) and the TS-I (0 MPa), respectively.

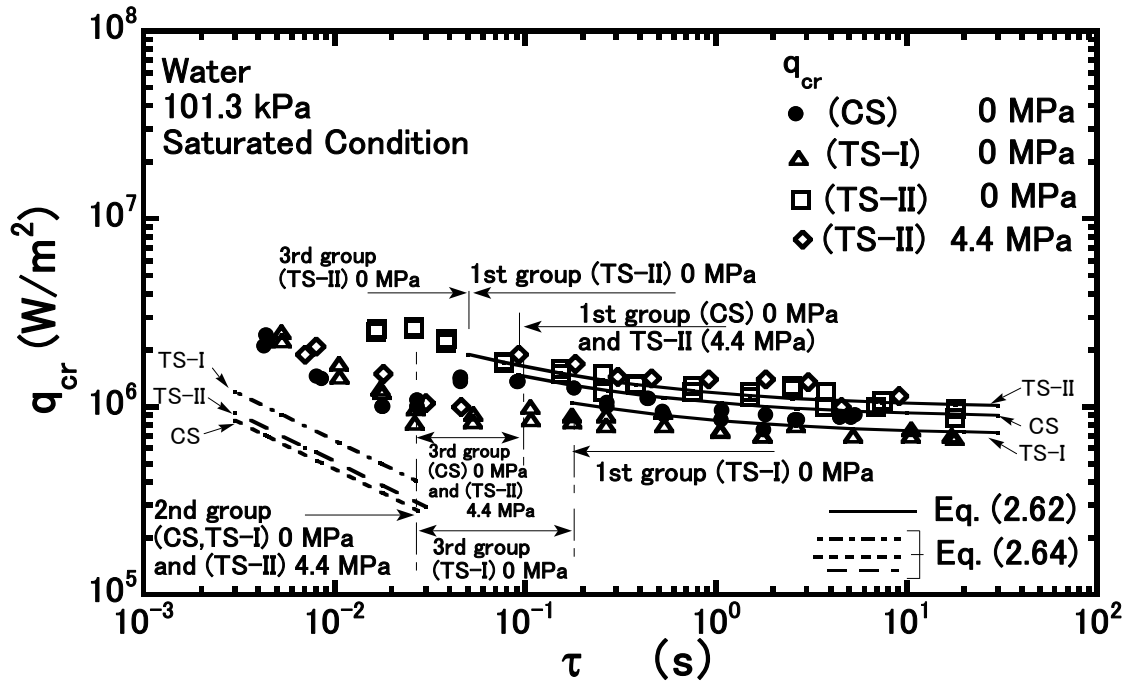


Fig. 5.8 Transient CHF for saturated conditions at atmospheric pressure with different surfaces

The first groups of CHF were tested with the previous corresponding values as shown in Eq. (2.62) suggested by [16] which is based on hydrodynamic instability model [38, 40], plotted with the solid lines. The Eq. (2.62) is the relation of quasi-steady-state CHF at subcooling, $q_{cst,sub}$, and period, τ . In this study, zero-subcooling is considered for the saturated condition.

The second group of CHF was occurred at the periods shorter than the periods corresponding to minimum CHF which is shown in Fig.5.8. The second groups of CHF attained only for the CS (0 MPa), the TS-I (0 MPa) and the TS-II (4.4 MPa) were induced by the semi-direct transition process that belongs to the typical heat transfer process as shown in Fig.5.6. The trend of the second groups of CHF for the CS (0 MPa), the TS-I (0 MPa) and TS-II (4.4 MPa) are similar and increase asymptotically. However, a quite higher trend is observed on the TS-II (4.4 MPa).

They were evaluated by the previous CHF data as described by Eq. (2.64) [16] which compromised with the heat flux at boiling initiation for certain condition or direct transition to film boiling. The Eq. (2.64) is based on the conduction heat transfer coefficient, h_c , for exponential heat input, experimental surface superheat at boiling initiation due to HSN in transient conduction regime, ΔT_i , and the liquid subcooling, ΔT_{sub} . The value of h_c which is indicated in Eq. (2.65) has the equivalent function of $(k_l \rho_l c_{pl} / \tau)^{1/2}$ at the condition of $(t/\tau \geq 3)$ [61]. In this study, the heat transfer coefficient versus $(t/\tau \geq 3)$ for period, τ , of 20 ms can be seen in Fig.5.4. As depicted in Fig.10, the correlation does not correspond to the measured second group of CHF. It is caused by the facts that the occurrence of nucleate boiling for a while gives to an increase of the heat flux. In this study, as the ΔT_i of the TS-I (0 MPa) is higher than the others, the corresponding value according to the Eq. (2.64) for TS-I (0 MPa) which is illustrated by chain-line is higher than the other ones.

The third group of CHF for period was induced by the heat transfer processes due to insufficient FDNB which belongs to the experiment results of the CS (0 MPa), the TS-I (0 MPa), the TS-II (0 MPa) and the TS-II (4.4 MPa) as shown in Fig. 5.7. It was usually occurred on the region from the maximum CHF of the first group down to the minimum one of the second group. However, that of the TS-II (0 MPa) was found at the short period. The third group of CHF for period due to the TS-I (0 MPa) is longer than the CS (0 MPa) and the TS-II (4.4 MPa). The third group of CHF for period from higher trend to lower

one are on the order of the TS-II (0 MPa), the TS-II (4.4 MPa), the CS (0 MPa) and the TS-I (0 MPa), respectively.

5.7 Summary

The experimental study on transient boiling heat transfer and critical heat flux on horizontal vertically oriented ribbons having different surfaces with CS, TS-I and TS-II in pool of water were carried out under saturated conditions at 101.3 kPa. The TS-II was subjected to the conditions without pre-pressurization and with pre-pressurization up to 4.4 MPa before each experimental run.

(1) The relation of the measured surface roughness and contact angle on CS, TS-I and TS-II agree with the previous corresponding relation based on the surfaces of copper and stainless steel.

(2) By pre-pressurization, the ΔT_i due to HSN which is depending on surface condition can be induced at boiling initiation even for quasi-steadily increasing heat input. The ΔT_i due to HSN does not affect to the CHF at the longer period. However, it affects to the CHF at the short exponential periods and the heat transfer process can lead to film boiling without a nucleate boiling.

(3) The heat transfer processes of TS-II (4.4 MPa) have the same transitions with the TS-I (0 MPa) and the CS (0 MPa) in short and intermediate exponential periods.

(4) For the same heat flux at each nucleate boiling regime, the TS-II (0/4.4 MPa) enhance the heat transfer $\sim 290\%$ and $\sim 430\%$ relative to the CS (0 MPa) and the TS-I (0 MPa) by calculating with the Eqs. (5.3) and (5.5).

(5) The transient CHF, q_{cr} , on the shorter periods are higher than the longer ones because the heat transfer process of the short period at the non-boiling regime is influenced by the transient conduction and it can generate the higher value of CHF.

(6) Based on the measured first group of CHF for period, TS-II (0/4.4 MPa) contributes the higher CHF of about 1.2 times and 1.5 times when compared with those of CS

(0 MPa) and TS-I (0 MPa), respectively.

(7) Transient CHF, q_{cr} , for short periods on the CS (0 MPa), the TS-I (0 MPa) and the TS-II (4.4 MPa) are higher than the corresponding values.

Chapter 6

Effect of Boiling Initiation due to Heterogeneous Spontaneous Nucleation on Transient Critical Heat Flux

6.1 Introduction

In this study, transient boiling CHF on horizontal vertically- oriented ribbon in pool of water at atmospheric and saturated condition on surface roughness of $0.22 \pm 0.02 \mu\text{m}$ and wettability, θ , value of $51.5 \pm 0.7^\circ$ due to exponentially increasing heat inputs was studied at pressure and subcooling. The ribbon heater having (4-mm wide, 0.2-mm thick and 41-mm long) were utilized. The two cases of pre-pressures such as with and without pre-pressure up to 4.4 MPa were carried out before each experimental run.

6.2 Experimental conditions

The experimental conditions for the effect of boiling initiation due to heterogeneous spontaneous nucleation on transient critical heat flux on horizontal vertically-oriented ribbon is indicated in Table. 6.1.

Table 6.1 Experimental conditions for the effect of boiling initiation due to heterogeneous spontaneous nucleation on transient critical heat flux

Parameter	Treated Surface
Liquid	Water
Heat Input (Q)	$Q_0 \exp(t/\tau)$
Pressure	101.3 - 297 kPa
ΔT_{sub}	0 - 30 K
τ	5 ms - 20 s
Pre-pressure	4.4 MPa
Material	Platinum
L (length)	41 mm
W (Width)	4 mm
Thickness	0.2 mm
R_a	$0.220 \pm 0.02 \mu\text{m}$
θ	$51.5 \pm 0.7^\circ$

6.3 Effect of pre-pressurization to time dependence of surface temperature, heat flux and heat generation rate

The time dependence of surface temperature, T_s , heat flux, q , and Heat Generation Rate, Q , versus pre-pressurization is shown in Fig. 6.1. They were performed due to exponential heat input for the period, τ , of 9 s on horizontal vertically oriented ribbon heater in a pool of boiling water at 101.3 kPa. The heat generation rate, Q , increases exponentially for the whole process. However, T_s and incipient heat flux, q_i , increase along heat generation curve up to overshoot temperature at boiling initiation, T_{ov} , and q_i , respectively. Then, they decreases rapidly and again increases gradually up to the

CHF point. It is suggested that the phenomena such as T_{ov} and delayed q_i are due to the pre-pressurization up to 4.4 MPa.

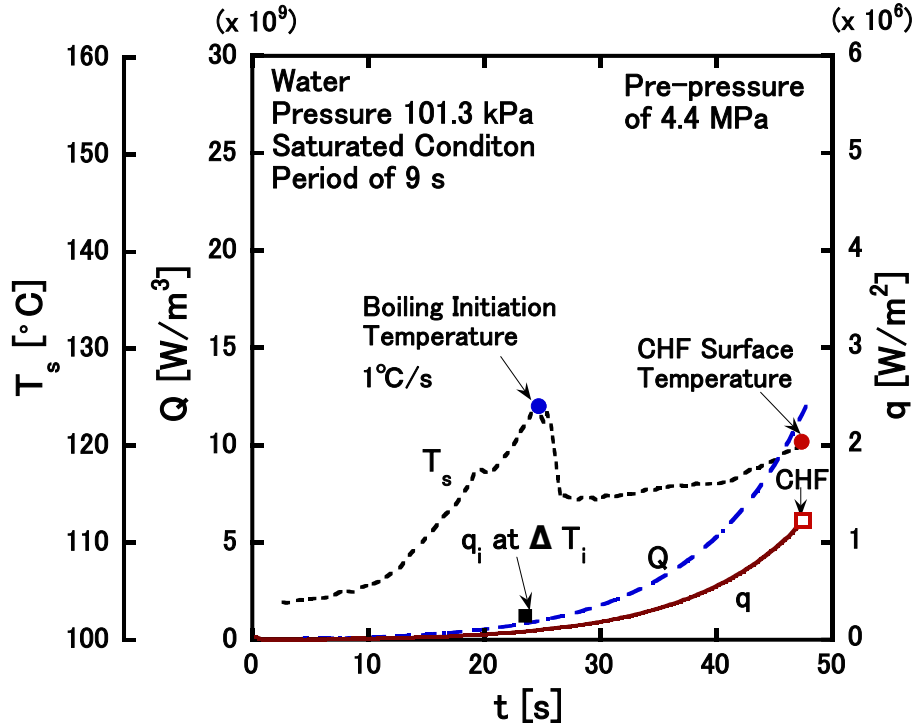


Fig. 6.1 Time dependence of surface temperature, heat flux and heat generation rate

6.4 Physical characteristic of boiling heat transfer due to pre-pressurization and exponential increasing heat inputs

The $h/q^{0.7}$ versus q for the period, τ , of 9 s, 100 ms and 20 ms were illustrated in Figs.6.2 and 6.3 for the conditions of without and with pre-pressurization, respectively.

Before boiling initiation, the factors of heat fluxes, $h/q^{0.7}$, decrease from higher value down to lower one for period, τ , of 9 s, 100 ms and 20 ms. After boiling initiation, they again increase to the higher values for the periods of 9 s and 100 ms. On the other hand, the $h/q^{0.7}$ due to $\tau = 100$ ms and $\tau = 20$ ms reaches up to the midway and suddenly decrease to the lower values, respectively.

Figures 6.4 and 6.5 shows $h/q^{0.7}$ versus ΔT_{sat} for the conditions of without and with pre-pressurization, respectively. The characteristic of $h/q^{0.7}$ versus ΔT_{sat} is the same to the characteristics of $h/q^{0.7}$ versus q as which were shown in Figs. 6.2 and 6.3.

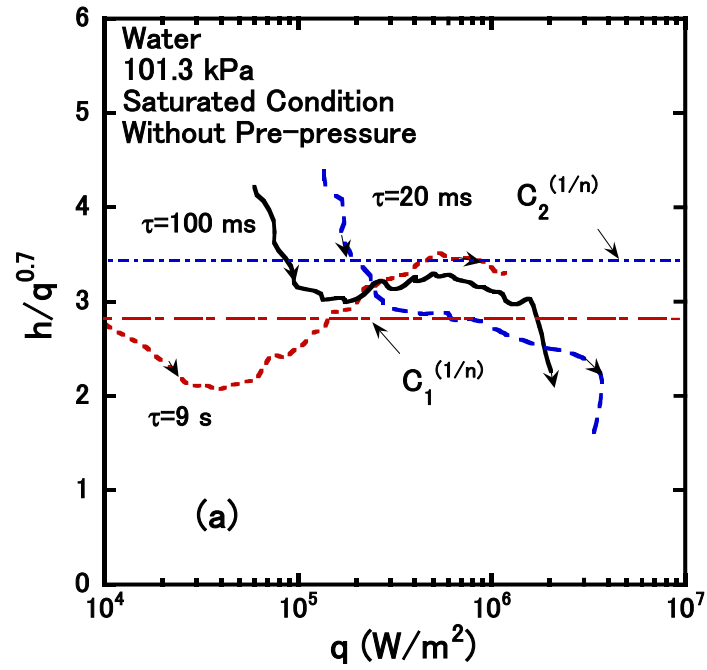


Fig. 6.2 The relation between $h/q^{0.7}$ and q as a parameter of period, τ , on the effect of without pre-pressurization

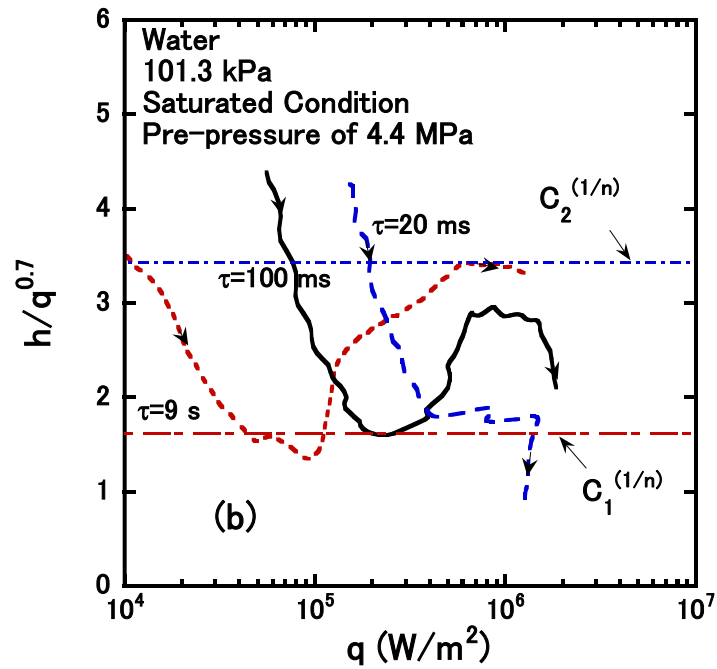


Fig. 6.3 The relation between $h/q^{0.7}$ and q as a parameter of period, τ , on the effect of with pre-pressurization

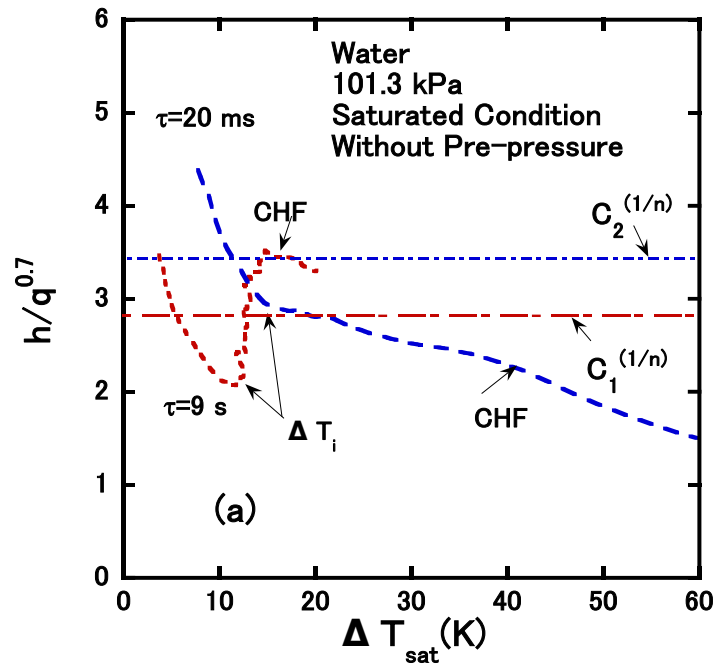


Fig. 6.4 The relation between $h/q^{0.7}$ and ΔT_{sat} as a parameter of period, τ , on the effect of without pre-pressurization

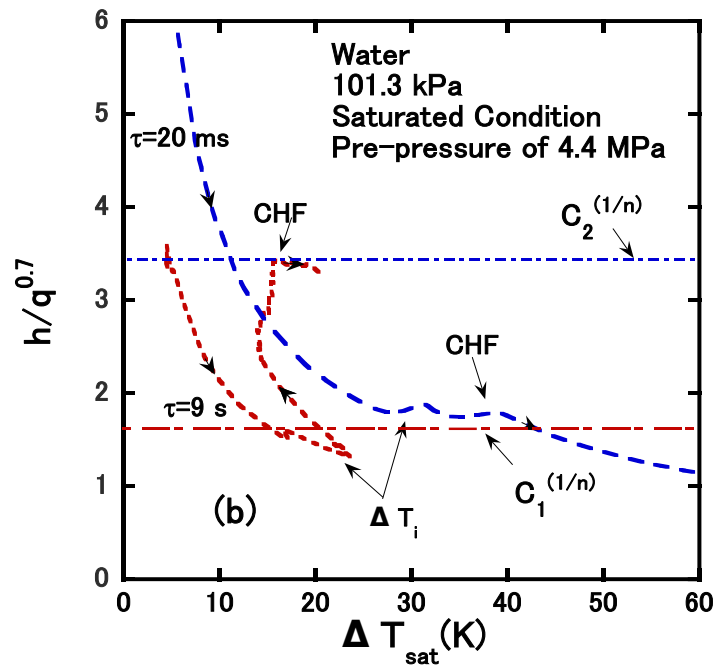


Fig. 6.5 The relation between $h/q^{0.7}$ and ΔT_{sat} as a parameter of period, τ , on the effect of with pre-pressurization

6.5 Developed empirical equations

The $C_1^{1/n}$ demonstrated by broken line represents the corresponding values for boiling initiation for without and with pre-pressurization, respectively, as shown in Figs. 6.2 - 6.5. The $C_2^{1/n}$ demonstrated by the chain line represents the corresponding values for the CHF due to fully developed nucleate boiling caused by period of 9 s, respectively, as shown in Figs. 6.2 - 6.5.

The value of $C_1^{1/n}$ for the condition of without pre-pressurization is larger than with pre-pressurization.

The following empirical equations for the heat flux at boiling initiation and nucleate boiling are obtained when the values of $C_1^{1/n}$ and $C_2^{1/n}$ are inserted into Eqs. (5.2) and (5.3),

$$q_i = 26.5\Delta T_i^{3.3} \quad (6.1)$$

$$q_{nb} = 56.7\Delta T_{sat}^{3.3} \quad (6.2)$$

$$q_i = 4.1\Delta T_i^{3.3} \quad (6.3)$$

$$q_{nb} = 56.7\Delta T_{sat}^{3.3} \quad (6.4)$$

Figure 6.6 shows the heat flux versus the surface superheat at boiling initiation for various exponential period for the case of subcooled water boiling from subcooling of 0 to 30 K at atmospheric pressure due to without pre-pressure. The experimental results were compared with Eq. (6.1) and Eq.(2.6). The Eq.(6.1) was obtained in the condition of saturated water boiling at atmospheric pressure. Moreover, the Eq.(2.6) is correlated based on the thermal boundary layer thickness in Hsu et al. [11]. According to this study, the influence of subcooling to surface superheat at boiling initiation is not very clear.

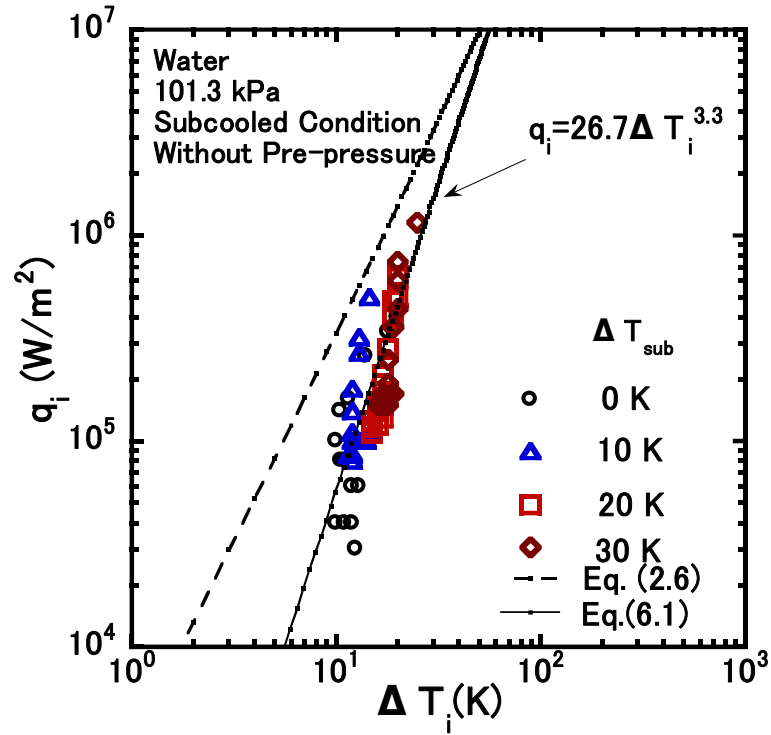


Fig. 6.6 The incipient heat flux versus the surface superheat at boiling initiation for various exponential period for the case of subcooled water boiling from subcooling of 0 K to 30 K at atmospheric pressure due to without pre-pressure

Figure 6.7 shows the heat flux versus the surface superheat at boiling initiation for various exponential period for the case of subcooled water boiling from subcooling of 0 to 30 K at atmospheric pressure due to with pre-pressure before each experimental run. The experimental results were compared with Eq. (6.3) and Eq.(2.6). Similar to the case of without pre-pressure, the influence of subcooling to surface superheat at boiling initiation is not very clear. The experimental results do not correlate significantly to Eq. (2.6). However, it would expect that the trend of experimental result at high heat flux will approach to the data of Eq. (2.6) as shown in Fig. 6.7.

The different values of surface superheat at boiling initiation for various period due to with and without pre-pressurization as shown in Fig. 6.6 and Fig. 6.7 come from different boiling mechanism. The larger surface superheat at boiling initiation is assumed to be due to heterogeneous spontaneous nucleation (HSN).

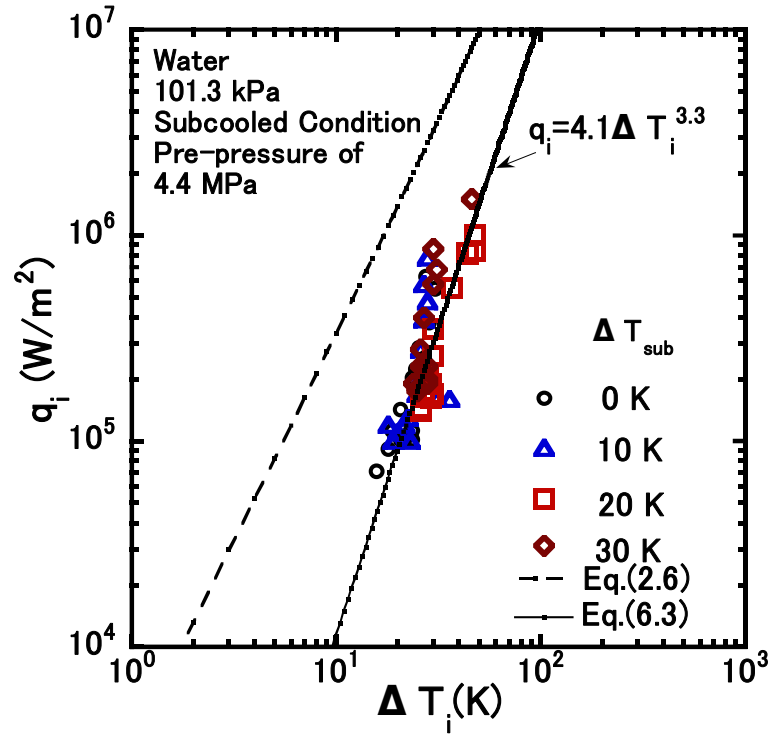


Fig. 6.7 The incipient heat flux versus the surface superheat at boiling initiation for various exponential period for the case of subcooled water boiling from subcooling of 0 K to 30 K at atmospheric pressure due to with pre-pressure

Figures 6.8 and 6.9 show the heat flux at boiling initiation, q_i , vs. surface superheat at boiling initiation, ΔT_i , for the conditions of without and with pre-pressurization, respectively, caused by exponentially increasing heat inputs from 9 s down to 20 ms. The solid circles are boiling initiation points and squares are CHF points. The heat transfer processes are depicted for the references of various boiling initiation and CHF points for period, respectively. As shown in figures, the surface superheats of boiling initiation caused by pre-pressurization are higher than without pre-pressurization. On the other hand, the CHF values according to the pre-pressurization is lower than the without pre-pressurization. The heat fluxes at boiling initiations by the correlations of various researchers are described in the figures. However, the correlations were considered by the steady heating. The HSN curve in the figures is larger than those correlations.

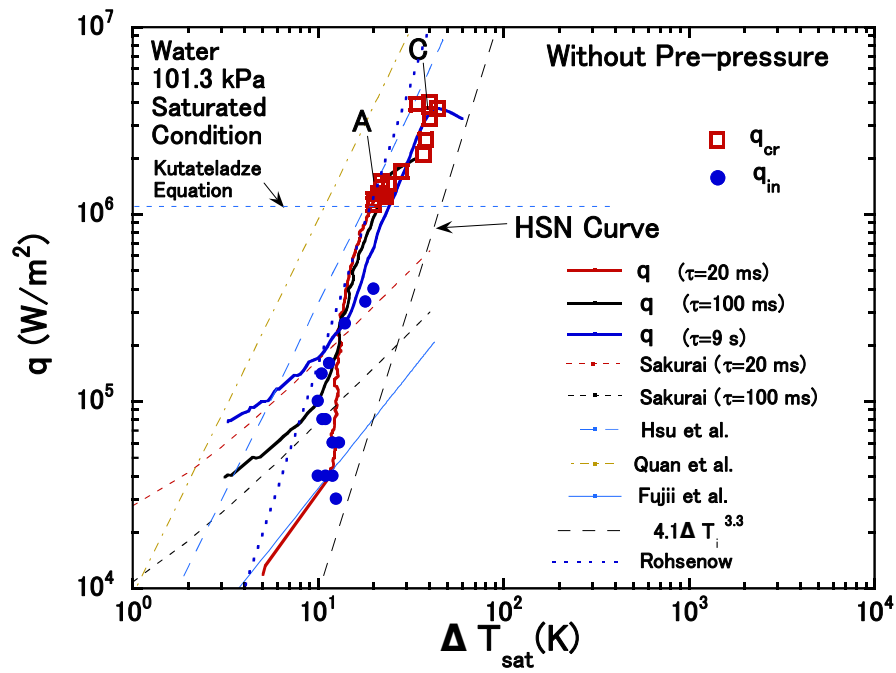


Fig. 6.8 The incipient heat fluxes and surface superheat at boiling initiation for the condition of without pre-pressurization

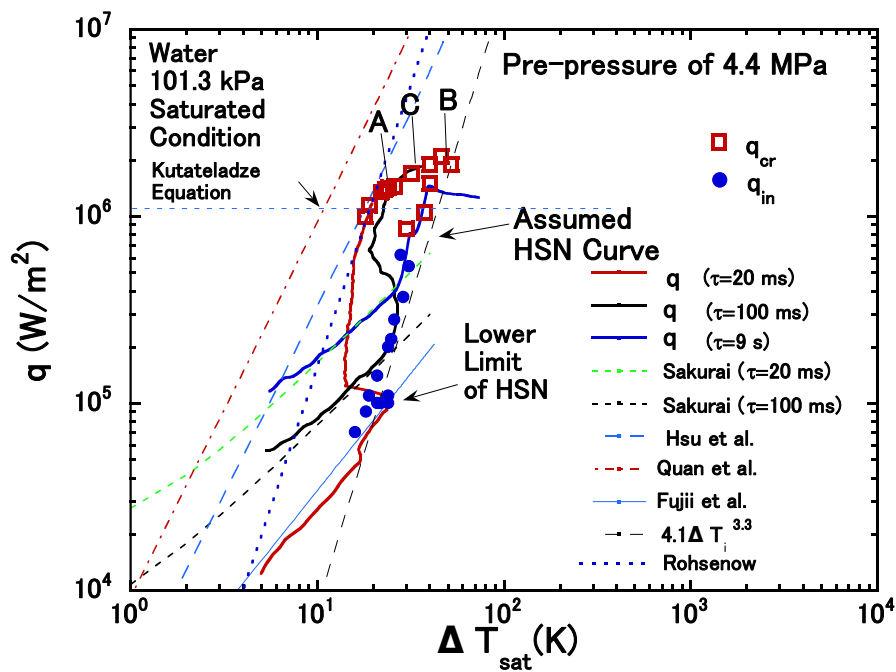


Fig. 6.9 The incipient heat fluxes and surface superheat at boiling initiation for the condition with pre-pressurization

6.6 Surface superheat at critical heat flux (CHF)

The relationship of the surface superheat at boiling initiation, ΔT_i , and the surface superheat at CHF, ΔT_c , for periods for the conditions of without and with pre-pressurization are shown in Fig.6.10. The ΔT_c is relatively larger than ΔT_i for the condition of without pre-pressurization. On the contrary, the ΔT_i and ΔT_c are similar results for the condition of with pre-pressurization. As mentioned above, as the ΔT_i for the condition of with pre-pressurization was considered corresponding to HSN, ΔT_c in this result is assumed to be HSN.

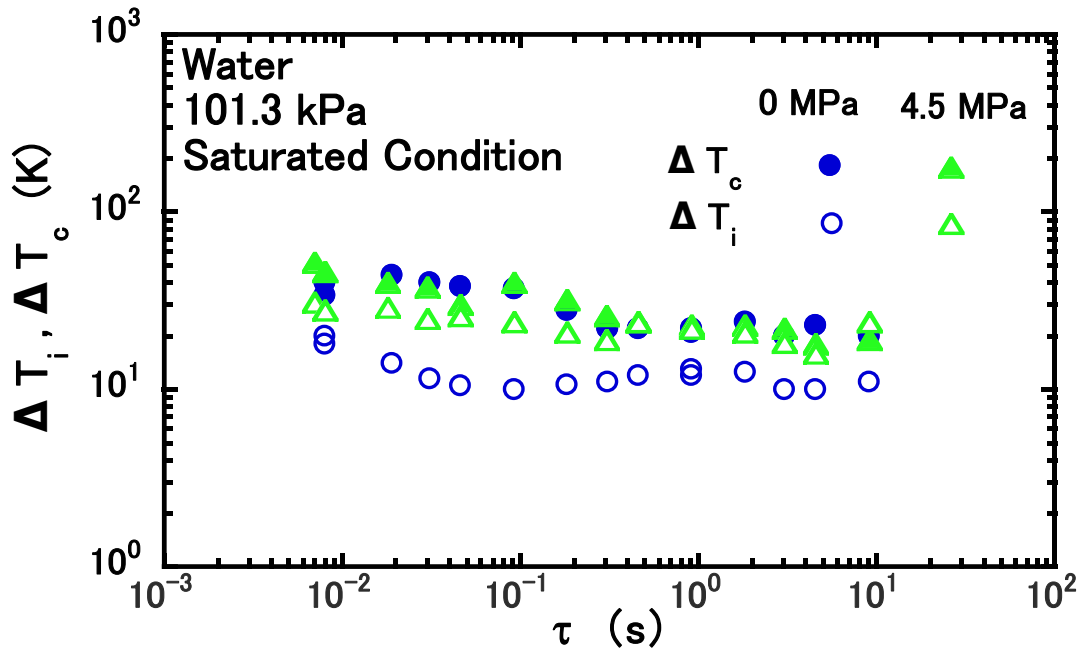


Fig. 6.10 Surface superheat at boiling initiation and CHF for the condition of without and with pre-pressurization

6.7 Transient CHF due to HSN

Figure 11 shows transient CHF, q_{cr} , versus the periods, τ , ranging from 10 ms to 20 s under saturated condition for the condition of without and with pre-pressurization. In this figure, the CHF, q_{cr} according to the condition of with pre-pressurization gradually increases to maximum CHF from steady-state one with a decrease in period, then, q_{cr} decreases down to minimum CHF and again q_{cr} increases with a decrease in period.

However, the q_{cr} for the condition of without pre-pressurization gradually increases with a decrease of period. The q_{cr} for the condition of with pre-pressurization can be divided into three groups as shown in figure; the 1st, the 2nd and the 3rd group CHF's for long, short and intermediate periods, respectively. The 1st group can be explained by the corresponding correlation of Eq. (2.62) plotted in solid lines. The 2nd group is higher than the correlation data of Eq. (2.64) shown by dotted lines. The first one is due to hydrodynamic instability (HI) and the second one is due to heterogeneous spontaneous nucleation (HSN).

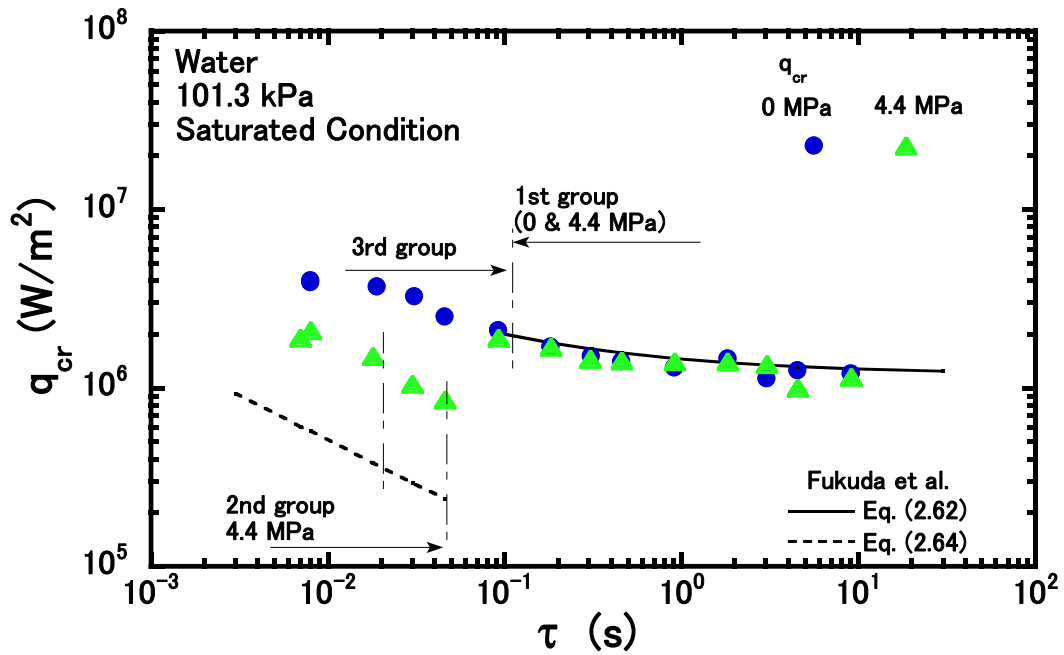


Fig. 6.11 Transient CHF for saturated condition at 101.3 kPa due to without and with pre-pressurization

Figures 6.12-6.14 shows transient CHF for period for various subcooling at pressures due to with and without pre-pressurization. The experimental results are examined with the previous correlations for the 1st and 2nd group equations, respectively. In the 1st group of CHF as shown in the figures corresponds to the 1st group correlation. The effect of subcooling reduces at higher pressure in the 1st group. There is no different values of CHF at the 1st group for with and without pre-pressurization. However, the CHF with the condition of pre-pressurization at shorter period approach to the second group equation.

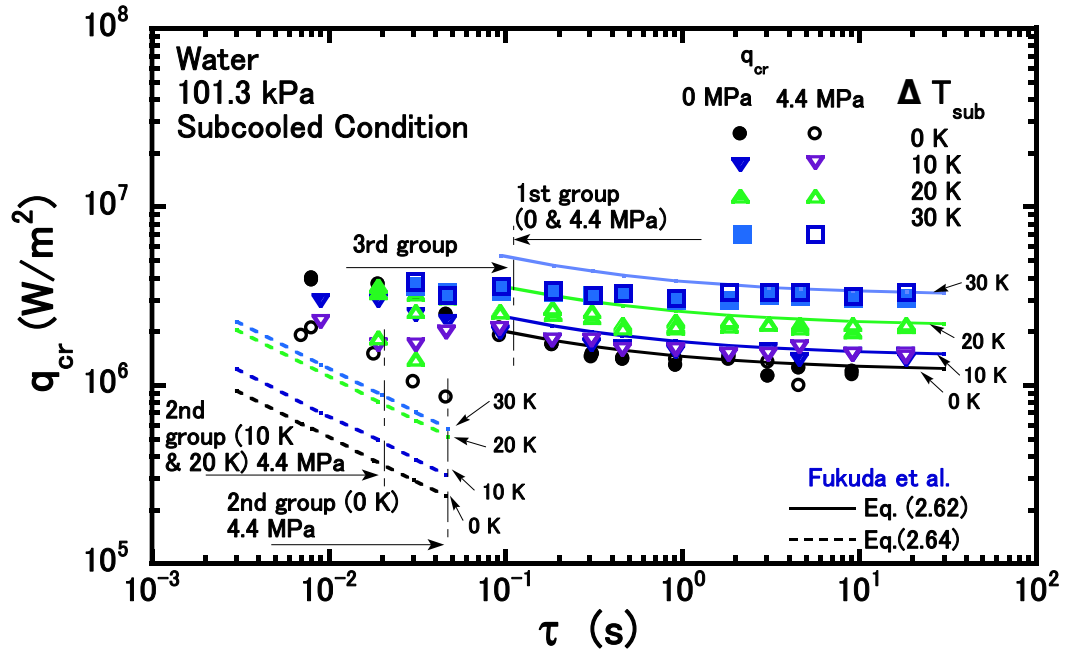


Fig. 6.12 Transient CHF for subcooled condition at 101.3 kPa due to without and with pre-pressurization

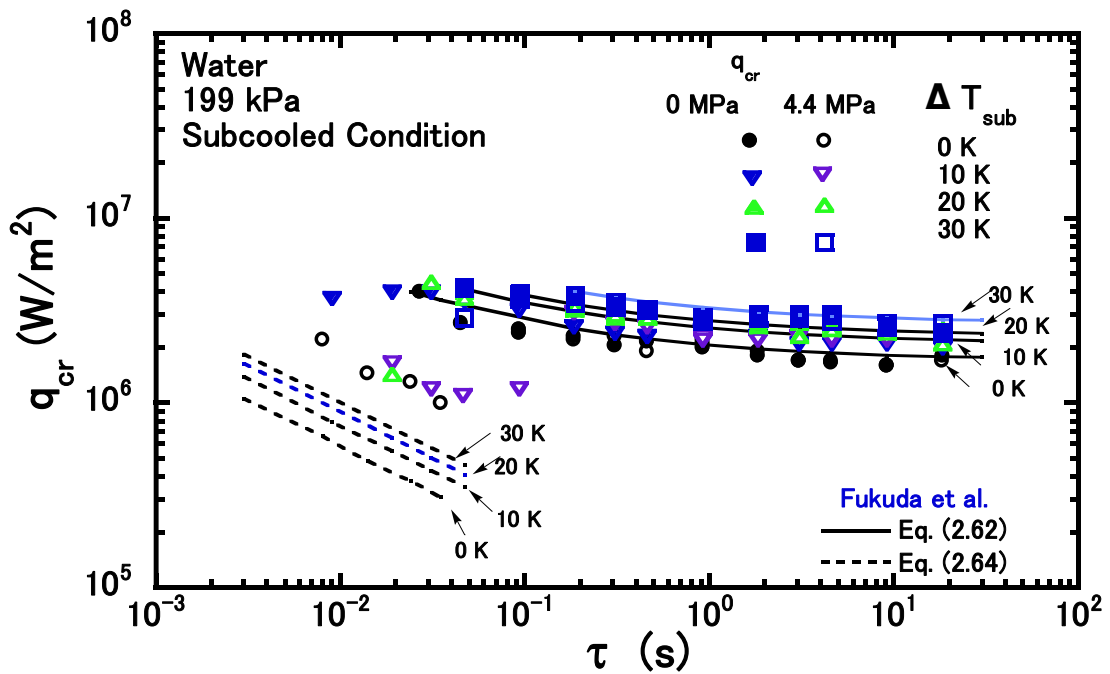


Fig. 6.13 Transient CHF for subcooled condition at 199 kPa due to without and with pre-pressurization

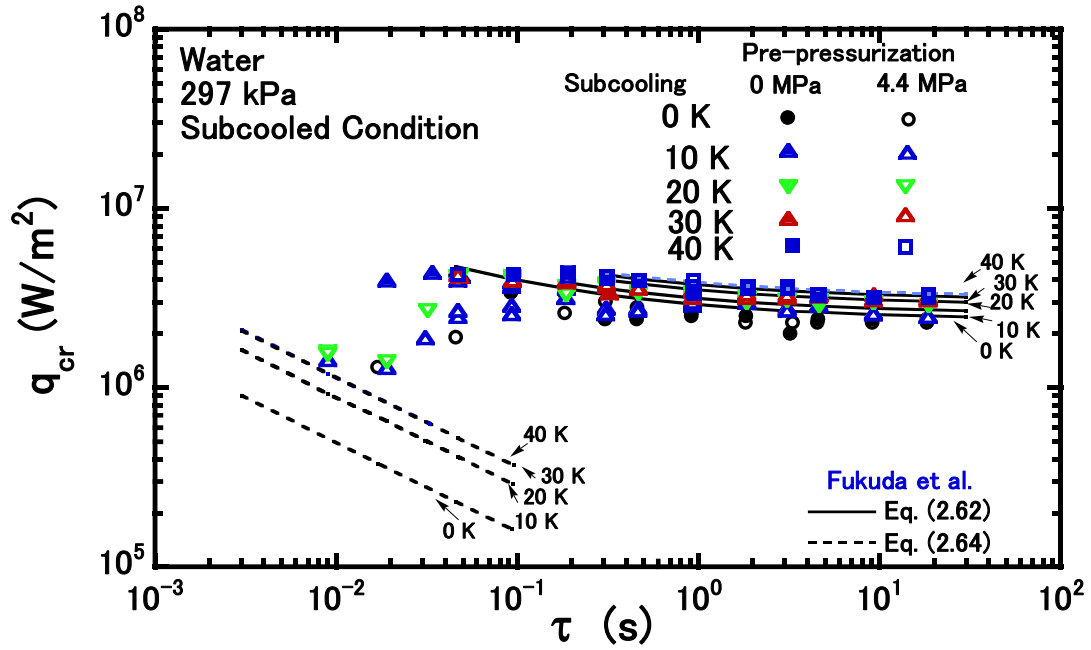


Fig. 6.14 Transient CHF for subcooled condition at 297 kPa due to without and with pre-pressurization

6.8 Summary

Effect of pre-pressurization on horizontal vertically oriented ribbon heater has been performed.

- (1) It was occurred that ΔT_i was induced by the active as well as flooded cavities. The flooded cavities depend on pre-pressurization. The boiling initiation mechanism caused by flooded cavities is assumed to be HSN which is also depending on surface condition.
- (2) It was assumed that the ΔT_i due to HSN induced the transient CHF which corresponds to the HSN mechanism. In this study, only transient CHF due to HSN was occurred at the shorter period.

Chapter 7

Conclusions

The experimental investigation of transient CHF on horizontal vertically oriented platinum ribbon with the effect of surface roughness, contact angle, exponential period, pressure, subcooling and pre-pressurization is carried out in water pool boiling. The heat generation rate is designed according to the exponential increasing heat input.

The three kinds of platinum ribbon, namely, commercial surface (CS), treated surface-I (TS-I) and treated surface-II (TS-II) have prepared having different surface roughness and contact angle. TS-II has the largest surface roughness and TS-I has the smallest surface roughness. Moreover, TS-II possessed the lowest contact angle and TS-I has the largest contact angle. The relation of surface roughness and contact angle were compromised with Kandlikar's observation [64].

Non-boiling heat transfer has been performed with TS-I for typical one. Non-boiling heat transfer increases with the decrease of period. At long period, they were become approximately the same value. They were compromised with respective natural convection, transient conduction and combined natural convection and transient equations.

The steady state CHF of TS-I has been tested with non-linear pool boiling CHF data and experimental data obtained on horizontal vertically oriented ribbon with commercial surface. The CHF values of TS-I were not reached to non-linear CHF data and experimental data of commercial surface. CHF due to heterogeneous spontaneous nucleation (HSN) was suggested instead of hydrodynamic instability (HI).

It is clear that the surface superheat of TS-I from heat transfer processes are larger than others.

Transient CHF of CS, TS-I and TS-II were performed at saturated boiling under atmospheric pressure. The test heater with the largest surface roughness and the smallest contact angle revealed the largest CHF. The transient CHF at long period in this research for different surfaces agree with the previous Sakurai and Fukuda's equation. The

transient CHF at short period are higher than the previous Sakurai-Fukuda's correlation. The same result were obtained for the transient CHF for pressure and subcooling which were carried out only for TS-I.

The values of CHF were tested with the CHF correlation in which the pure hydrodynamic model is added with the effect of orientation and contact angle. The experimental results TS-II and CS in this study are higher than the corresponding values. Although the CHF value of TS-I is higher than the corresponding value, it is in the acceptable trend. As this correlation was postulated based on the assumption of smooth surface, it is assumed that the values of TS-II and CS are higher than the correlation or the experimental results of CS, TS-I and TS-II were free from orientation effect.

As it is important to know the occurrence of heterogeneous spontaneous nucleation (HSN) which can degrade CHF. In this aspects, boiling initiation on TS-II was examined with various pre-pressurization rate. It was clearly revealed that boiling initiated from two mechanisms. Boiling from flooded cavity was due to heterogeneous spontaneous nucleation.

Moreover, the heat transfer processes for the condition of with pre-pressurization converted to the heat transfer processes of TS-I in transient heat transfer test. Rohsenow's nucleate boiling heat transfer is comparable to the heat transfer processes of fully developed nucleate regime obtained at the CS, TS-I and TS-II, respectively. Interestingly, the TS-II agreed exactly. It was found that as the heat input rate was long, the effect of pre-pressurization becomes reduce to the CHF.

The heat flux of boiling initiation due to heterogeneous nucleation by previous correlations could not correlate the onset of boiling for various period in this research especially for the condition of pre-pressurization. Therefore, the heat flux at boiling initiation due to heterogeneous spontaneous nucleation (HSN) was correlated empirically.

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