Influence of Test Tube Material on Subcooled Flow Boiling Critical Heat Flux in Short Vertical Tube*

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Abstract
The steady state subcooled flow boiling critical heat flux (CHF) for the flow velocities ($u=4.0$ to $13.3$ m/s), the inlet subcoolings ($\Delta T_{sub,in}=48.6$ to $154.7$ K), the inlet pressure ($P_{in}=735.2$ to $969.0$ kPa) and the increasing heat input ($Q_0\exp(t/\tau)$, $\tau=10$, 20 and 33.3 s) are systematically measured with the experimental water loop. The 304 Stainless Steel (SUS304) test tube of inner diameter ($d=6$ mm), heated length ($L=66$ mm) and $L/d=11$ with the inner surface of rough finished (Surface roughness, $Ra=3.18$ µm), the Cupro Nickel (Cu-Ni 30%) test tube of $d=6$ mm, $L=60$ mm and $L/d=10$ with $Ra=0.18$ µm and the Platinum (Pt) test tubes of $d=3$ and 6 mm, $L=66.5$ and 69.6 mm, and $L/d=22.2$ and 11.6 respectively with $Ra=0.45$ µm are used in this work. The CHF data for the SUS304, Cu-Ni 30% and Pt test tubes were compared with SUS304 ones for the wide ranges of $d$ and $L/d$ previously obtained and the values calculated by the authors’ published steady state CHF correlations against outlet and inlet subcoolings. The influence of the test tube material on CHF is investigated into details and the dominant mechanism of subcooled flow boiling critical heat flux is discussed.

Key words: Critical Heat Flux, Subcooled Flow Boiling, Test Tube Material

1. Introduction
The influence of test tube material on steady state subcooled flow boiling critical heat flux (CHF) is necessary to investigate the reliability of a divertor in a nuclear fusion facility. The divertor is made of copper alloy tube or copper alloy block whose thermal conductivity is very high.

Divavin et al. (1) carried out the high heat flux experiments on rectangular samples with cylindrical cooling ducts with one-side heating to the effect of a porous coating deposed on inner cooled surface on the Incident Critical Heat Flux (ICHF) performance at water subcooled boiling regime. The different materials of samples were under consideration as well: stainless steel, copper and copper alloys. They defined the empirical correlation between ICHF at one-side heating condition and geometrical parameters of elements of cooling design.

The heat load tests have been under way by the electron beam heating on a divertor...
element which consists of the carbon armors joined to the copper heat-sink with a cooling tube. A helical type fusion experimental device which is Large Helical Device (LHD) located in the National Institute for Fusion Science, Japan, has two types of divertor element. One is Mono-block type (Cylindrical one), the other is Flat-plate type (Rectangular one). The Mono-block type divertor is made of the oxygen-free copper cooling tube with 10 mm inner diameter and 1.5 mm thickness, and the carbon armor (CX2002U) with 33 mm outer diameter and 10 mm thickness. The cooling tube is located in the center of the carbon armor. The carbon armor is brazed to the cooling tube. On the other hand, the Flat-plate type one is made of the oxygen-free copper block of 30 mm wide by 25 mm high and the carbon tile (CX2002U) of 30 mm wide by 10 mm high. The carbon tile is brazed to the copper block. The cooling tube with the inner diameter of 10 mm is horizontally located at the height of 17 mm from the lower surface on the central line of the copper block.

The critical heat flux (CHF) experiments for the different geometries (smooth tube, finned swirl tube, screw tube and hypervapotron) were performed in the thermal hydraulic conditions of fusion reactors: one-side heating, high heat flux and water-cooled by JAEA (Japan Atomic Energy Agency) (3). Test sections were made of two different materials: Cu (0.2%Ag) and OFHC-Cu (Oxygen Free High Conductivity Copper).

Recently, three-dimensional thermal measurements for a one-side-heated mono-block were made for the robust design of one-side-heated plasma-facing components and other high heat flux components by Boyd et al. (10). The mono-block test sections were fabricated from Type AL-15 Glidcop Grade Copper.

On the other hand, many researchers have experimentally studied the CHFs on the uniformly heated stainless steel test tube by a steadily increasing current for the most part (5)-(11). We have already measured the steady state CHFs, \( q_{\text{ex,sub,in}} \) (2229 points) on the uniformly heated SUS304 test tubes by a steadily increasing current for wide ranges of experimental conditions to establish the database for designing the divertor of a helical type fusion experimental device, which is a Large Helical Device (LHD) located in the National Institute for Fusion Science, Japan (12)-(19). It has been clarified that the \( q_{\text{ex,sub,in}} \) against \( \Delta T_{\text{sub,out}} \) for \( \Delta T_{\text{sub,out}} \geq 30 \) K are almost proportional to \( d^{0.4} \) and \( d^{0.4} \) for fixed \( \Delta T_{\text{sub,out}} \) and \( L/d \), to \( (\Delta T_{\text{sub,out}})^{0.7} \) for a fixed \( L/d \), and to \( (L/d)^{0.1} \) for a fixed \( \Delta T_{\text{sub,out}} \) based on the experimental data (12)-(19). We have given the following steady state CHF correlations against outlet and inlet subcoolings based on the effects of test tube inner diameter \( d \), flow velocity \( u \), outlet and inlet subcoolings \( (\Delta T_{\text{sub,out}} \text{ and } \Delta T_{\text{sub,in}}) \) and ratio of heated length to inner diameter \( (L/d) \) on CHF:

\[
Bo = 0.082 \left( \frac{d}{\sqrt{\sigma/g(\rho_1 - \rho_v)}} \right)^{0.1} \frac{g}{\rho_v} \frac{L}{d} \left( \frac{L}{d} \right)^{0.1} \frac{Sc}{\sqrt{Sc^*}}
\]

for outlet subcooling \( (\Delta T_{\text{sub,out}} \geq 30 \) K) \hspace{1cm} (1)

\[
Bo = C_1 \left( \frac{d}{\sqrt{\sigma/g(\rho_1 - \rho_v)}} \right)^{0.1} \frac{g}{\rho_v} \frac{L}{d} \left( \frac{L}{d} \right)^{0.1} e^{-\frac{(L/d)}{C_2 \sqrt{Sc^*}\rho_v}}
\]

for inlet subcooling \( (\Delta T_{\text{sub,in}} \geq 40 \) K) \hspace{1cm} (2)

where \( C_1 = 0.082, C_2 = 0.53 \) and \( C_3 = 0.7 \) for \( L/d \) around 40 and \( C_1 = 0.092, C_2 = 0.85 \) and \( C_3 = 0.9 \) for \( L/d \) around 40. \( Bo \), \( We \), \( Sc \) and \( Sc^* \) are boiling number \( (= q_{\text{ex,sub,in}}/(\rho_v g h_{fg}) \) \), Weber number \( (= g d^2/\rho_v \sigma) \), non-dimensional outlet subcooling \( (= \rho_c/\Delta T_{\text{sub,out}}/h_{fg}) \) and non-dimensional inlet subcooling \( (= \rho_c/\Delta T_{\text{sub,in}}/h_{fg}) \) respectively. Saturated thermo-physical properties were evaluated at the outlet pressure. The correlations against outlet and inlet subcoolings can describe the authors’ published steady state CHF data (2229 points) for wide ranges of test tube inner diameters \( (d=2 \) to 12 mm), heated lengths \( (L=22 \) to 149.7 mm), \( L/d \) around 40, and \( \text{outlet pressures} \) \( (P_{\text{out}}=159 \) kPa to 1.1 MPa), flow velocities \( (u=4.0 \) to 13.3 m/s) and dissolved oxygen concentration \( (O_2=8.63 \) to 0.0087 ppm) within 15 % difference for outlet...
subcoolings ($\Delta T_{\text{sub,out}}=30$ to 140 K) and inlet subcoolings ($\Delta T_{\text{sub,in}}=40$ to 151 K) on test tubes with rough, smooth and mirror finished inner surfaces (surface roughness, $Ra=3.18, 0.26$ and 0.14 µm), although the CHF data (32 points) with the mirror finished inner surface ($Ra=0.14$ µm) are distributed within -30 to +7.6 % difference of Eq. (1) for 71.4 K $\leq \Delta T_{\text{sub,out}} \leq 108.4$ K.

And furthermore, we have given the following transient CHF correlation against inlet subcooling for the exponentially increasing heat inputs with wide range of exponential periods, $\tau$, ($Q=Q_0 \exp(t/\tau)$, $\tau=19.04$ ms to 8.3 s) based on the effect of the non-dimensional period clarified in the work (198 points) for the SUS304 test tubes of the inner diameters of 3 and 6 mm, the heated lengths of 66.5 and 60 mm and $L/d=22.2$ and 10 with mirror and rough finished inner surfaces ($Ra=0.14$ and 3.18 µm) respectively at the outlet pressures of around 800 and 1100 kPa (20)-(23).

$$Bo=C_1 \left[ \frac{d}{\sqrt{g/\rho_1 - \rho_2}} \right]^{-4.1} We^{0.5} \left( \frac{L}{d} \right)^{-0.1} e^{-\frac{(L/d)}{(C_2 Re)^{0.5}}} \frac{Sc \times \sigma}{\sqrt{g/\rho_1 - \rho_2}} \left[ 1 + 1.4 \left( \frac{\tau u}{\sqrt{g/\rho_1 - \rho_2}} \right) \right]^{-4.6}$$

for inlet subcooling ($\Delta T_{\text{sub,in}} \geq 40$ K) (3)

Most of the data (198 points) are within 15 % difference of Eq. (3).

Recently, the steady state CHFs and the heat transfer coefficients (HTCs) in subcooled flow boiling were applied to thermal analyses of the Flat-plate type divertor and the Mono-block type one of a helical type fusion experimental device (LHD). The incident CHF, $q_{\text{cr,inc}}$, for the Flat-plate type divertor with the cooling tube diameter, $d$, of 10 mm and the plate width, $w$, ranging from 16 to 30 mm and for the Mono-block type divertor with the cooling tube diameter, $d$, of 10 mm and the carbon armor outer diameter, $D$, of 26 and 33 mm were numerically analyzed based on the measured steady state CHFs, $q_{\text{cr,sub,st}}$, and HTCs with the test tube inner diameter, $d$, of 9 mm and the heated length, $L$, of 48 to 149 mm for the SUS304 test tube. And the ratio of the one-side heat loading data, $q_{\text{cr,inc}}$, to the uniform heat loading data, $q_{\text{cr,sub,st}}$, has been represented as the simple equation based on the numerical solutions (24)-(26). However, the divertor for a nuclear fusion facility will be made of copper alloy tube or copper alloy block for the most part, not of stainless steel ones.

The objectives of present study are fourfold. First is to measure the steady state CHF for test tubes of different wall materials with copper alloy (SUS304, Cu-Ni 30% and Pt) in the wide range of outlet and inlet subcoolings and flow velocity. Second is to clarify the influence of test tube material on the steady state subcooled flow boiling CHF. Third is to confirm the applicability of the steady state CHF correlations against outlet and inlet subcoolings, Eqs. (1) and (2), based on the experimental data by using the thin SUS304 test tube. Fourth is to discuss the mechanisms of subcooled flow boiling critical heat flux in short vertical tube.

**Nomenclature**

- $Bo = q_{\text{cr,sub}}/Gh_{fg}$, boiling number
- $C_1, C_2, C_3$, constant in Eqs. (2) and (3)
- $c$, specific heat, J/kg K
- $c_p$, specific heat at constant pressure, J/kg K
- $d$, test tube inner diameter, m
- $G = \rho u$, mass flux, kg/m$^2$s
- $g$, acceleration of gravity, m/s$^2$
- $h = (\rho x \lambda)^{0.5}$, thermal activity factor, J/m$^2$K$^{0.5}$
- $h_{fg}$, latent heat of vaporization, J/kg
- $I$, current flowing through standard resistance, A
- $L$, heated length, m
\( L_e \) entrance length, m
\( L_{opt} \) distance between inlet pressure transducer and inlet of the heated section, m
\( O_2 \) dissolved oxygen concentration, ppm
\( P_{in} \) pressure at inlet of heated section, kPa
\( P_{opt} \) pressure measured by inlet pressure transducer, kPa
\( P_{out} \) pressure at outlet of heated section, kPa
\( P_{opt} \) pressure measured by outlet pressure transducer, kPa
\( Q \) heat input per unit volume, W/m\(^3\)
\( Q_0 \) initial exponential heat input, W/m\(^3\)
\( q \) heat flux, W/m\(^2\)
\( q_{cr,inc} \) incident critical heat flux, W/m\(^2\)
\( q_{cr,sub} \) transient critical heat flux for subcooled condition, W/m\(^2\)
\( q_{cr,sub,st} \) steady state critical heat flux for subcooled condition, W/m\(^2\)
\( r_i \) test tube inner radius, m
\( r_o \) test tube outer radius, m
\( R_1 \) to \( R_3 \) resistance in a double bridge circuit, \( \Omega \)
\( Ra \) average roughness, \( \mu \)m
\( Re = \frac{Gd}{\mu} \), Reynolds number
\( R_{max} \) maximum roughness depth, \( \mu \)m
\( R_z \) mean roughness depth, \( \mu \)m
\( S \) surface area, m\(^2\)
\( S_c = \frac{ctc \Delta T_{sub,out}/hfg}{∆T_{sub,out}} \), non-dimensional outlet subcooling
\( S_c^* = \frac{ctc \Delta T_{sub,in}/hfg}{∆T_{sub,in}} \), non-dimensional inlet sub-cooling
\( T \) temperature, K
\( T_{in} \) inlet liquid temperature, K
\( T_{out} \) outlet liquid temperature, K
\( T_s \) heater inner surface temperature, K
\( T_{sat} \) saturation temperature, K
\( t \) time, s
\( \Delta T_{sub,in} = (T_{sat} - T_{in}) \), inlet liquid subcooling, K
\( \Delta T_{sub,out} = (T_{sat} - T_{out}) \), outlet liquid subcooling, K
\( u \) flow velocity, m/s
\( V \) volume, m\(^3\)
\( We = \frac{G^2d/\rho \sigma}{\rho} \), Weber number
\( \delta \) wall thickness, mm
\( \lambda \) thermal conductivity, W/mK
\( \rho \) density, kg/m\(^3\)
\( \rho_e \) electrical resistivity, \( \mu \Omega \)m
\( \sigma \) surface tension, N/m
\( \tau \) exponential period, s

**Subscript**

\( cr \) critical heat flux
\( g \) vapor
\( in \) inlet
\( out \) outlet
\( l \) liquid
\( sub \) subcooled conditions
\( wnh \) with no heating

### 2. Experimental Apparatus and Method

The schematic diagram of experimental water loop comprised of the pressurizer is
shown in Fig. 1. The loop is made of SUS304 stainless steel and is capable of working up to 2 MPa. The loop has five test sections whose inner diameters are 2, 3, 6, 9 and 12 mm. Test sections were vertically oriented with water flowing upward. The two test sections of the inner diameters of 3 and 6 mm were used in this work. The circulating water was distilled and deionized with about 5-MΩ cm specific resistivity. The circulating water through the loop was heated or cooled to keep a desired inlet temperature by pre-heater or cooler. The flow velocity was measured by a mass flow meter using a vibration tube. The flow velocity was controlled by regulating the frequency of the three-phase alternating power source to the canned type circulation pump. The water was pressurized by saturated vapor in the pressurizer in this work. The pressure at the inlet of the test tube was controlled within ±1 kPa of a desired value by using a heater controller of the pressurizer.

The cross-sectional view of 6 mm inner diameter test section used in this work is shown in Fig. 2. The SUS304 test tubes with 3 different surface roughness have been generally used. The test tubes with rough and smooth finished inner surfaces (RF and SF) are
The rough finished inner surface was fabricated by annealing the test tubes first in the atmosphere of air and was then acidized, while the smooth finished inner surface was fabricated by annealing the test tubes in the atmosphere of hydrogen gas. The smooth finished inner surface test tube was polished up to around 25 µm deep by the electrolytic abrasive treatment to realize the mirror finished one (MF). Three different material test tubes which were the SUS304 test tube with the rough finished inner surface (SUS304-RF), Cupro Nickel one with the commercial finish of inner surface (Cu-Ni 30%) and Platinum one with the commercial finish of inner surface (Pt) were mainly used in this work. Wall thicknesses of the test tubes, δ, were 0.2, 0.3, 0.4 and 0.5 mm. The inner surface conditions of the test tube were observed by the SEM photograph and inner surface roughness was measured by Tokyo Seimitsu Co., Ltd.’s surface texture measuring instrument (SURFCOM 120A). The silver-coated 5-mm thickness copper-electrode-plates to supply heating current were soldered to the surfaces of the both ends of the test tube. The both ends of test tube were electrically isolated from the loop by Bakelite plates of 14-mm thickness. The test tubes were also thermally insulated from atmosphere with a Bakelite block of 120 mm wide, 80 mm deep and L mm high.

The test tube was heated with an exponentially increasing heat input supplied from a direct current source (Takasago Ltd., NL035-500R, DC 35 V-3000 A) through the two copper electrodes shown in Fig. 3. The common specifications of the direct current source are as follows. Constant-voltage (CV) mode regulation is 0.005 %+3 mV of full scale, CV mode ripple is 500 µV r.m.s. or better and CV mode transient response time is less than 200 µsec (Typical) against 5 % to full range change of load. At the CHF, the test tube average temperature rapidly increases. The current for the heat input to the test tube was automatically cut off when the measured average temperature increased up to the preset temperature, which was several tens of Kelvin higher than corresponding CHF surface temperature. This procedure avoided actual burnout of the test tube.

The transient average temperature of the test tube was measured with resistance thermometry participating as a branch of a double bridge circuit for the temperature measurement. The output voltages from the bridge circuit together with the voltage drops across the two electrodes and across a standard resistance were amplified and then were sent via a D/A converter to a digital computer. These voltages were simultaneously sampled at a constant time interval ranging from 60 to 200 ms. The average temperature of the test tube was calculated with the aid of previously calibrated resistance-temperature relation. The heat generation rate in the test tube was calculated from the measured voltage difference between the potential taps of the test tube and the standard resistance. The surface heat flux is the difference between the heat generation rate per unit surface area and the rate of change of energy storage in the test tube obtained from the fairied average temperature versus time curve as follows:

\[
q(t) = \frac{V}{S} \left[ Q(t) - \rho c \frac{dT}{dt} \right]
\]

where \(\rho\), \(c\), \(V\) and \(S\) are the density, the specific heat, the volume and the inner surface area of the test tube, respectively. The inner surface temperature was also obtained by solving the heat conduction equation in the test tube under the conditions of measured average temperature and surface heat flux of the test tube. The temperature of the heater surface, \(T_s\), can be described as follows:

\[
T_s = \frac{q_r}{4(r_i^2 - r_e^2)\lambda} \left[ 4r_i^2 \left( \frac{\ln r_e}{2} - \frac{\ln r_i}{2} \right) - (r_i^2 - r_e^2) \right] - \frac{q_r}{2(r_i^2 - r_e^2)\lambda} \left( r_i^2 - 2r_i^2 \ln r_i \right)
\]

In case of the 6 mm inner diameter test section, before entering the test tube, the test water flows through the tube with the same inner diameter of the test tube to form the fully developed velocity profile. The entrance tube lengths, \(L_e\), are given 333 mm (\(L_e/d=55.5\)).
The values of $L_e/d$ for $d=6$ mm in which the center line velocity reaches 99% of the maximum value for turbulence flow were obtained ranging from 9.8 to 21.9 by the correlation of Brodkey and Hershey (27) as follows:

$$
\frac{L_e}{d} = 0.693 R_e^{1/4}
$$

(6)

The inlet and outlet liquid temperatures were measured by 1-mm o.d., sheathed, K-type thermocouples which are located at the centerline of the tube at the upper and lower stream points of 283 and 63 mm from the tube inlet and outlet points. The inlet and outlet pressures were measured by the strain gauge transducers, which were located near the entrance of conduit at upper and lower stream points of 63 mm from the tube inlet and outlet points. The thermocouples and the transducers were installed in the conduits as shown in Fig. 2. The inlet and outlet pressures of the test tube were calculated from the pressures measured by inlet and outlet pressure transducers as follows:

$$
P_{in} = P_{opt} - \left( P_{opt} - P_{x,y} \right) \frac{L}{0.063 + L}
$$

(7)

$$
P_{out} = P_{in} - \left( P_{in} - P_{opt} \right) \frac{L}{0.063 + L}
$$

(8)

Experimental errors are estimated to be ±1 K in inner tube surface temperature and ±2% in heat flux. Inlet flow velocity, inlet and outlet subcoolings, inlet and outlet pressures, and exponential period were measured within the accuracy ±2%, ±1 K, ±1 kPa and ±2% respectively.

3. Experimental Results and Discussion

3.1 Experimental Conditions

The initial experimental conditions such as inlet flow velocity, inlet and outlet subcoolings, inlet and outlet pressures, and exponential period for the flow boiling CHF experiments were determined independently each other before each experimental run.

The experimental conditions were as follows:

- **Heater Material**: SUS304, Cu-Ni 30% and Pt
- **Inner Diameter ($d$)**: 6 mm for SUS304 and Cu-Ni 30% test tubes and 3 and 6 mm for Pt ones
- **Heated Length ($L$)**: 66 mm for SUS304 test tube, 60 mm for Cu-Ni 30% one, and 66.5 and 69.6 mm for Pt ones
- **$L/d$**: 11 for SUS304 test tube, 10 for Cu-Ni 30% one, and 22.2 and 11.6 for Pt ones
- **Wall Thickness ($\delta$)**: 0.2, 0.3 and 0.5 mm for SUS304 test tubes, 0.3 and 0.5 mm for Cu-Ni 30% ones, and 0.5 and 0.4 mm for Pt ones
- **Surface Condition**: Rough finished inner surface for SUS304 test tube and commercial finish of inner surface for Cu-Ni 30% and Pt ones
- **Surface roughness for SUS304, Cu-Ni 30% and Pt test tubes**: 3.18, 0.18 and 0.45 μm for $Ra$, 27.28, 1.26 and 2.93 μm for $R_{max}$ and 21.16, 1.04 and 1.93 μm for $R_z$
- **Inlet flow velocity ($u$)**: 4.0, 6.9, 9.9 and 13.3 m/s
- **Inlet Pressure ($P_{in}$)**: 735.2 to 969.0 kPa
- **Outlet Pressure ($P_{out}$)**: 703.3 to 928.5 kPa
- **Inlet Subcooling ($\Delta T_{sub,in}$)**: 48.6 to 154.7 K
- **Outlet Subcooling ($\Delta T_{sub,out}$)**: 23.4 to 119.1 K
- **Inlet Liquid Temperature ($T_{in}$)**: 288.9 to 396.9 K
- **Steadily Increasing Heat Input ($Q$)**: $Q_0 \exp(t/\tau)$, $\tau$ = 10, 20 and 33.3 s

3.2 Steady State CHF

3.2.1 In case of 304 Stainless Steel test tube
Figure 4 shows the SEM photograph of the 304 Stainless Steel (SUS304) test tube with rough finished inner surface (RF). The inner surface roughness is measured 3.18 µm for Ra, 27.28 µm for Rmax and 21.16 µm for Rz respectively.

The subcooled flow boiling critical heat flux (CHF) for the flow velocities (u=4.0 to 13.3 m/s), the inlet subcoolings (ΔTsub,in=48.6 to 154.7 K) and the inlet pressure (P_{in}=735.2 to 969.0 kPa) are systematically measured with the increasing heat input (Q_0 \exp(t/\tau), \tau=10, 20 and 33.3 s). The CHF are almost constant for the exponential period ranging from 10 to 33.3 s for the same experimental conditions. The steady state CHFs, q_{cr,sub,st}, against outlet subcoolings for the inner diameter of 6 mm with the heated length of 66 mm at the outlet pressure of around 800 kPa are shown versus the outlet subcoolings measured, ΔT_{sub,out}, with the flow velocities of 4.0, 6.9, 9.9 and 13.3 m/s in Fig. 5. The outlet subcooling, ΔT_{sub,out}, averaged over the cross sectional area was obtained from the measured outlet liquid temperature, T_{out}, and outlet pressure, P_{out}. The figure illustrates the trends in the variation of CHF with increasing outlet subcooling. The CHFs for the ΔT_{sub,out} increase with an increase in ΔT_{sub,out}. The increasing rate becomes lower for higher ΔT_{sub,out}. The CHFs become higher with an increase in flow velocity at a fixed ΔT_{sub,out}. These trends have been already reported by Hata et al. (12)-(19) on steady state CHF data for the inner diameters of 2, 3, 6, 9 and 12 mm with the heated lengths of 22 to 150 mm.

The relation between q_{cr,sub,st} and ΔT_{sub,out} shown in Fig. 5 are rewritten on q_{cr,sub,st} vs. ΔT_{sub,in} graph in Fig. 6 to know the influence of ΔT_{sub,in} on the steady state CHF for flow velocities from 4.0 to 13.3 m/s. The inlet subcooling, ΔT_{sub,in}, was obtained by the measured inlet liquid temperature, T_{in}, and inlet pressure, P_{in}. The CHFs for the ΔT_{sub,in} increase with an increase in ΔT_{sub,in}. The increasing rate becomes also lower for higher ΔT_{sub,in}. The values of CHF data show nearly the same trends of dependence on ΔT_{sub,out}, although the value of ΔT_{sub,in} at each CHF point is far higher than that of ΔT_{sub,out}.

Figures 7 and 8 show the ratios of the steady state CHF data obtained in this work (110 points) to the corresponding values calculated by Eqs. (1) and (2) versus ΔT_{sub, out} and ΔT_{sub, in}.

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Fig. 4 SEM photograph of SUS304 test tube with the rough finished inner surface.

Fig. 5 q_{cr,sub,st} vs. ΔT_{sub,out} for SUS304 test tube with an inner diameter of 6 mm and a heated length of 66 mm at an outlet pressure of 800 kPa.

Fig. 6 q_{cr,sub,st} vs. ΔT_{sub,in} for SUS304 test tube with an inner diameter of 6 mm and a heated length of 66 mm at pressures of 735 to 891 kPa.
respectively. Most of the data for 53 K ≤ ΔTsub,out ≤ 110 K are within ±15 % difference of Eq. (1) and those for 30 K < ΔTsub,out < 53 K are within -5 to +35 % difference. And, most of the data for the tested range of ΔTsub,in (48 K ≤ ΔTsub,in ≤ 140 K) are within 15 % difference of Eq. (2).

3.2.2 In case of Cupro Nickel test tube

Figure 9 shows the SEM photograph of the Cupro Nickel (Cu-Ni 30%) test tube with commercial finish of inner surface. The inner surface roughness is measured 0.18 µm for Ra, 1.26 µm for Rmax and 1.04 µm for Rz respectively. The values of Ra would become approximately 18 times as smooth as that of the SUS304 test tube with RF.

The steady state CHFs, qcr,sub,st, against outlet subcoolings for the inner diameter of 6 mm with the heated length of 60 mm at the outlet pressure of around 800 kPa are shown versus the outlet subcoolings measured, ΔTsub,out, with the flow velocities of 4.0, 6.9, 9.9 and 13.3 m/s.

Fig. 10 qcr,sub,st vs. ΔTsub,out for Cu-Ni 30% test tube

Fig. 11 qcr,sub,st vs. ΔTsub,in for Cu-Ni 30% test tube with an inner diameter of 6 mm and a heated length of 60 mm at an outlet pressure of 800 kPa.

Fig. 9 SEM photograph of the Cu-Ni 30% test tube.
13.3 m/s in Fig. 10. The CHF for the $\Delta T_{sub,out}$ increase with an increase in $\Delta T_{sub,out}$. The increasing rate also becomes lower for higher $\Delta T_{sub,out}$. The CHF also become higher with an increase in flow velocity at a fixed $\Delta T_{sub,out}$. The curves given by Eq. (1) at each flow velocity are shown in Fig. 10 for comparison. The CHF data are in good agreement with the values given by the correlation against outlet subcooling, Eq. (1).

The relation between $q_{cr,sub,st}$ and $\Delta T_{sub,out}$ is rewritten on $q_{cr,sub,st}$ vs. $\Delta T_{sub,in}$ graph in Fig. 11. The values of CHF data show nearly the same trends of dependence on $\Delta T_{sub,in}$, although the value of $\Delta T_{sub,in}$ for each CHF data is far higher than that of $\Delta T_{sub,out}$. The curves derived from CHF correlation against inlet subcooling, Eq. (2), are shown at each flow velocity for comparison in Fig. 11. The CHF data are in good agreement with the values given by Eq. (2) in the whole experimental range.

Figures 12 and 13 show the ratios of the CHF data (42 points) to the corresponding values calculated by Eqs. (1) and (2) versus $\Delta T_{sub,out}$ and $\Delta T_{sub,in}$ respectively. The ratios obtained with the authors’ correlations for $\Delta T_{sub,out}$ up to about 119.1 K and for $\Delta T_{sub,in}$ up to about 148.6 K were almost within ±15 % differences of unity.

3.2.3 In case of Platinum test tube

Figure 14 shows the SEM photograph of the Platinum (Pt) test tube with commercial finish of inner surface. The inner surface roughness is measured 0.45 µm for $Ra$, 2.93 µm for $R_{max}$ and 1.93 µm for $Rz$ respectively. It is confirmed from these photos that the Cupro Nickel test tube seems to be more flatly, although the cracks ranging from 1.0 to 3.0 µm extended vertically through the surface were observed clearly on the SUS304 test tube with RF and quite a number of deep cavities ranging from 1.0 to 3.0 µm were also observed on the Platinum test tube.

The steady state CHFs, $q_{cr,sub,st}$, for the inner diameter of 3 and 6 mm with the heated length of 66.5 and 69.6 mm respectively at the outlet pressure of around 800 kPa are

![Flow direction](image-url)
measured with the flow velocities of 4.0, 6.9, 9.9 and 13.3 m/s. The ratios of the measured steady state CHFs, \( q_{cr,sub,st} \), against outlet and inlet subcoolings for \( d=3 \) mm and \( L=66.5 \) mm, and \( d=6 \) mm and \( L=69.6 \) mm (23 points) to the corresponding CHFs calculated from Eqs. (1) and (2), \( \frac{q_{cr,sub,st}}{q_{cr,sub,st}} \), versus \( \Delta T_{sub,out} \) and \( \Delta T_{sub,in} \) are shown in Figs. 15 and 16 for the outlet pressure of around 800 kPa and the inlet pressures of 745 to 969 kPa, respectively. The ratios are within \(-24 \) to \(+17\%\) difference of Eq. (1) for the whole \( \Delta T_{sub,out} \) range tested here and within around \( \pm 15\%\) difference of Eq. (2) for the whole \( \Delta T_{sub,in} \) range tested here.

It will not be easy to complete wide distribution database for heat flux with platinum test tube in high pressure experimental condition by using the existing direct current source (DC 35 V-3000 A), because electrical resistivity of platinum, \( \rho_e \), is very small as shown in Table 1. The steady state CHFs, \( q_{cr,sub,st} \), for the inner diameter of 6 mm with the heated length of 66.5 mm at the outlet pressure of around 800 kPa were first measured at the outlet subcooling of around 60 K with the flow velocity of 4.0 m/s in this work and the \( q_{cr,sub,st} \) for the inner diameter of 3 mm with the heated length of 69.6 mm were secondly measured for the wide range of outlet and inlet subcoolings and flow velocity to confirm the applicability of CHF correlations against outlet and inlet subcoolings, Eqs. (1) and (2) for Pt test tube.

3.3 Discussion

Hata et al. (12)-(16),(19) have clarified that the steady state CHFs, \( q_{cr,sub,st} \), against \( \Delta T_{sub,out} \) for \( \Delta T_{sub,out} \geq 30 \) K are almost proportional to \( d^{-0.4} \) and \( u^{0.4} \) for fixed \( \Delta T_{sub,out} \) and \( L/d \), to \( (\Delta T_{sub,out})^{0.7} \) for a fixed \( L/d \) and to \( (L/d)^{0.1} \) for a fixed \( \Delta T_{sub,out} \) based on the experimental data by using the thin SUS304 test tube. And, the steady state CHF correlations against outlet and inlet subcoolings, Eqs. (1) and (2), mentioned above have been given based on the effects of test tube inner diameter (\( d \)), flow velocity (\( u \)), outlet and inlet subcoolings (\( \Delta T_{sub,out} \) and \( \Delta T_{sub,in} \)) and ratio of heated length to inner diameter (\( L/d \)) on steady state CHF for the SUS304 test tube. And furthermore, the influence of dissolved gas concentration, inner surface roughness and heating rate on the heat transfer characteristics and the CHFs are investigated in detail for the SUS304 test tubes of \( d=3 \) and 6 mm and \( L=66.5 \) and 60 mm with the inner surfaces of rough, smooth and mirror finished (\( Ra=3.18, 0.26 \) and 0.14 \( \mu m \)) (17),(18),(20)-(23).

3.3.1 Influence of surface roughness

The critical heat flux (CHF) of subcooled water flow boiling for the SUS304 test tubes of the inner-diameter (\( d=3 \) mm), the heated length (\( L=66.5 \) mm) and \( L/d=22.17 \) with the inner surfaces of rough, smooth and mirror finished (\( Ra=3.18, 0.26 \) and 0.14 \( \mu m \)) were systematically measured for the dissolved oxygen concentration (\( O_2 \)) of 8.63 to 0.0288 ppm.
Table 1 Thermo-physical properties of SUS304, Cu-Ni 30% and Pt.

<table>
<thead>
<tr>
<th></th>
<th>T (K)</th>
<th>c (J/KgK)</th>
<th>λ (W/mK)</th>
<th>ρ (Kg/m³)</th>
<th>h (J/m²Ks⁰.5)</th>
<th>ρₚ (µΩm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS304</td>
<td>300</td>
<td>372.6</td>
<td>16.0</td>
<td>7920</td>
<td>6871</td>
<td>0.706</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>389.4</td>
<td>19.0</td>
<td>7810</td>
<td>7602</td>
<td>0.930</td>
</tr>
<tr>
<td>Cu-Ni 30%</td>
<td>300</td>
<td>410.8</td>
<td>29.8</td>
<td>8947</td>
<td>10464</td>
<td>0.399</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>458.0</td>
<td>43.9</td>
<td>8828</td>
<td>13323</td>
<td>0.415</td>
</tr>
<tr>
<td>Pt</td>
<td>300</td>
<td>133</td>
<td>71.4</td>
<td>21460</td>
<td>14276</td>
<td>0.105</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>141</td>
<td>73.0</td>
<td>21280</td>
<td>14799</td>
<td>0.216</td>
</tr>
</tbody>
</table>

with the flow velocities (\(u=4.0\) to 13.3 m/s), the inlet subcoolings (\(∆T_{sub,in}=68.15\) to 158.11 K), the outlet subcoolings (\(∆T_{sub,out}=25.69\) to 126.43 K), the inlet pressure (\(Pin=740.67\) to 975.58 kPa) and the outlet pressure (\(P_{out}=738.51\) to 936.40 kPa) under the saturated vapor pressure (18).

The CHFs on rough, smooth, and mirror finished inner surfaces for the lowest dissolved oxygen concentration are shown versus the surface roughness, \(Ra\), with the flow velocity as a parameter in Fig. 17. The \(q_{cr,sub,st}\) for each flow velocity are almost constant independently of the surface roughness (\(Ra=3.18\) to 0.14 µm). The corresponding curves for each flow velocity obtained from Eq. (2) are also shown in the figure. The \(q_{cr,sub,st}\) for the SUS304 test tubes with \(Ra=3.18\) to 0.14 µm are well expressed by the equation. No Influence of the surface roughness on CHFs was observed on the inner surface test tubes with \(Ra=3.18\) to 0.14 µm. The range of \(Ra\) for the SUS304 test tube of \(d=3\) mm is a little wider than that in this work (\(Ra=3.18\) µm for the SUS304 test tube, \(Ra=0.18\) µm for Cu-Ni 30% one and \(Ra=0.45\) µm for Pt one).

3.3.2 Influence of test tube material

The thermo-physical properties of SUS304, Cu-Ni 30% (28) and Pt are shown in Table 1. It can be seen in the Table that the thermal conductivities for Cupro Nickel and Platinum are about 2 and 4.5 times as large as that for the SUS304 respectively. It was assumed before the experiment that the steady state CHFs, \(q_{cr,sub,st}\) for the Cupro Nickel and Platinum test tubes may become larger than the values derived from Eqs. (1) and (2) due to the following two reasons. One is that the steady-state heat conduction in the longitudinal direction of Cupro Nickel and Platinum tubes with the same thickness will be larger than that for the
SUS304 one at a fixed heat flux level. This may cause smaller temperature difference between inlet and outlet for the Cupro Nickel and Platinum tubes. Another is that the occurrence of local heat spot at the critical heat flux may be suppressed by the increased transient conduction heat from the nearby surface area. However, the steady state CHF correlation against outlet subcooling, Eq. (1), can almost describe the data for the Cupro Nickel test tube with $d=6$ mm and $L=60$ mm within ±15 % difference at 46.4 K≤Δ$T_{sub,out}$≤119.1 K and those for the Platinum one with $d=3$ mm and $L=66.5$ mm, and $d=6$ mm and $L=69.6$ mm within -24 to +17 % difference at 59.7 K≤Δ$T_{sub,out}$≤109.5 K. And the steady state CHF correlation against inlet subcooling, Eq. (2), can also describe most of the data for Cupro Nickel one at 68.8 K≤Δ$T_{sub,in}$≤148.6 K and those for Platinum one at 87.5 K≤Δ$T_{sub,in}$≤154.7 K within 15 % difference. For the SUS304 test tube with $d=6$ mm and $L=66$ mm, Eqs. (1) and (2) have also described the data within ±15 % difference at 53 K≤Δ$T_{sub,out}$≤110 K and within -5 to +35 % difference at 30 K<Δ$T_{sub,out}$<53 K, and within ±15 % difference at 48 K≤Δ$T_{sub,in}$≤140 K, respectively.

It was assumed that the magnitude of the subcooled CHF would be affected considerably by that of the thermal conductivity and the heat capacity for the test tube material difference. The steady state CHFs on the SUS304, Cu-Ni 30% and Pt test tubes for $ΔT_{sub,in}$=90 K are shown versus the thermal activity factor (29), $h$, with the flow velocity as a parameter in Fig. 18. The $q_{cr,sub,st}$ for each flow velocity are almost constant independently of the thermal activity factor ($h=7554.1$ to 14726 J/m²Ks⁰.⁵). The corresponding curves for each flow velocity obtained from Eq. (2) are also shown in the figure. The $q_{cr,sub,st}$ are well expressed by the equation for the test tube material difference. Changes of test tube material showed very little effect on steady state CHF under wide range of outlet and inlet subcoolings and flow velocity. It is expected based on this fact that Eqs. (1) and (2) will give the general correlations for steady state CHF against outlet and inlet subcoolings for the commercially obtainable pipes with various thermo-physical properties.

4. Conclusions

The steady state critical heat flux (CHF) of subcooled water flow boiling for the 304 Stainless Steel (SUS304) test tube of $d=6$ mm and $L=66$ mm and $L/d=11$ with the inner surface of rough finished (Surface roughness, $Ra=3.18$ μm), the Cupro Nickel (Cu-Ni 30%) test tube of $d=6$ mm, $L=60$ mm and $L/d=10$ with $Ra=0.18$ μm and the Platinum (Pt) test tubes of $d=3$ and 6 mm, $L=66.5$ and 69.6 mm, and $L/d=22.2$ and 11.6 respectively with $Ra=0.45$ μm are systematically measured for the flow velocities ($u=4.0$ to 13.3 m/s), the inlet subcoolings ($ΔT_{sub,in}=48.6$ to 154.7 K), the outlet subcoolings ($ΔT_{sub,out}=23.4$ to 119.1 K), the inlet pressure ($P_{in}=735.2$ to 969.0 kPa) and the outlet pressure ($P_{out}=703.3$ to 928.5 kPa) under the saturated vapor pressure. Experimental results lead to the following conclusions.

(1) Most of the CHF data for SUS304 test tube with rough finished inner surface (110 points) are within ±15 % difference of Eq. (1) for 53 K≤Δ$T_{sub,in}$≤110 K and those are within -5 to +35 % difference for 30 K<Δ$T_{sub,in}$<53 K. And, most of the data for the tested range of $ΔT_{sub,in}$ (48 K≤Δ$T_{sub,in}$≤140 K) are within 15 % difference of Eq. (2).

(2) Most of the data for Cu-Ni 30% test tube with commercial finish of inner surface (42 points) are almost within ±15 % differences of Eqs. (1) and (2) for $ΔT_{sub,out}$ up to about 119.1 K and for $ΔT_{sub,in}$ up to about 148.6 K.

(3) Most of the data for Pt test tube with commercial finish of inner surface (23 points) are almost within -24 to +17 % difference of Eq. (1) for 59.7 K≤Δ$T_{sub,out}$≤109.5 K and within around ±15 % difference of Eq. (2) for 87.5 K≤Δ$T_{sub,in}$≤154.7 K.

(4) Changes of test tube material for 304 stainless steel, Cupro Nickel and Platinum with the thermal activity factor ($h=7554.1$ to 14726 J/m²Ks⁰.⁵) showed very little effect on steady state CHF under wide range of outlet and inlet subcoolings and flow velocity. It is
assumed based on this fact that Eqs. (1) and (2) will give the general correlations for steady state CHF against outlet and inlet subcoolings for the commercially obtainable pipes with various thermo-physical properties.

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