Critical Heat Fluxes of Subcooled Water Flow Boiling against Inlet Subcooling in Short Vertical Tube*

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The critical heat fluxes (CHF) of subcooled water flow boiling for the test tube inner diameters ($d = 3$ and 6 mm) and the heated lengths ($L = 67, 120$ and 150 mm) are systematically measured for the flow velocities ($u = 4.0$ to 13.3 m/s), the inlet subcoolings ($\Delta T_{sub,in} = 48$ to 148 K), the outlet subcoolings ($\Delta T_{sub,out} = 10.5$ to 95.1 K), the inlet pressure ($P_{in} = 753$ to 995 kPa) and the outlet pressure ($P_{out} = 720$ to 887 kPa). The SUS304 tubes of $L = 67, 120$ and 150 mm for $d = 3$ mm and $L = 150$ mm for $d = 6$ mm are used. The values of L/d are 22, 40 and 50 for $d = 3$ mm, and 25 for $d = 6$ mm, respectively. The CHF, $q_{cr,sub}$, for a fixed $\Delta T_{sub,out}$ become gradually lower with an increase in the L/d in the whole experimental range. The CHF correlation against outlet subcooling, which has been previously derived for L/d lower than 16, was modified to new one containing the L/d effect based on these experimental data. Furthermore, the relation between $q_{cr,sub}$ and L/d for a fixed $\Delta T_{sub,in}$ was checked. The values of $q_{cr,sub}$ for a fixed $\Delta T_{sub,in}$ became exponentially lower with the increase in L/d . CHF correlation against inlet subcooling has been given based on the experimental data for L/d ranging from 4.08 to 50. The correlations against outlet and inlet subcoolings can describe not only the CHF obtained in this work for the inner diameter of 3 and 6 mm at the outlet pressure of around 800 kPa but also the authors' published CHF data (1611 points) for the wide ranges of $P_{in} = 159$ kPa to 1 MPa, $d = 3$ to 12 mm, $L = 33$ to 150 mm and $u = 4.0$ to 13.3 m/s within 15% difference for $30 \text{ K} \leq \Delta T_{sub,out} \leq 140 \text{ K}$ and $40 \text{ K} \leq \Delta T_{sub,in} \leq 151 \text{ K}$.

Key Words: Critical Heat Flux, Subcooled Flow Boiling, Inlet Subcooling, Short Vertical Tube

1. Introduction

The knowledge of the critical heat fluxes (CHF) of subcooled water flow boiling in short vertical tube is important for the design of a divertor in a nuclear fusion facility. We have already measured the CHF, $q_{cr,sub}$, for wide range of experimental conditions to establish the database for designing the divertors for a helical type fusion experimental device, which is Large Helical Device (LHD) lo-

cated in National Institute for Fusion Science, Japan⁽¹⁾⁻⁽⁵⁾. And, we have given the CHF correlation against average outlet subcoolings based on the experimental data for four different test tubes with inner diameters, d , of 3, 6, 9 and 12 mm and heated lengths, L , of 33, 67, 99 and 133 mm respectively with $L/d = 11$.

$$Bo = 0.069 \left\{ \frac{d}{\sqrt{\sigma/g(\rho_l - \rho_g)}} \right\}^{-0.1} We^{-0.3} Sc^{0.7} \quad (1)$$

for outlet subcooling

where, Sc is non-dimensional outlet subcooling, $Sc = c_{pl}(\Delta T_{sub,out})_{cal}/h_{fg}$. The correlation can describe the authors' published CHF for the wide range of $P_{out} = 159$ kPa to 1 MPa, $d = 3, 6, 9$ and 12 mm, $L = 49, 99$ and 149 mm, $L/d = 4.08$ to 16.56 , $(\Delta T_{sub,out})_{cal} = -4$ to 130 K and $u = 4.0$ to 13.3 m/s within 15% difference for $50 \text{ K} \leq (\Delta T_{sub,out})_{cal} \leq 130 \text{ K}$ and within -10 to $+30\%$ for $30 \text{ K} < (\Delta T_{sub,out})_{cal} < 50 \text{ K}$.

The objectives of present study are threefold. First is

* Received 22nd October, 2003 (No. 03-4146)

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to measure the CHF's on inner side of a pipe with combinations of inner diameter ($d = 3$ and 6 mm) and tube length ($L = 67, 120$ and 150 mm) for wide ranges of flow velocity and inlet subcooling with $22 \leq L/d \leq 50$. Second is to confirm the applicability of the CHF correlation against outlet subcooling, Eq. (1), to the experimental data of q_{cr} for $22 \leq L/d \leq 50$. Third is to derive the CHF correlation against inlet subcooling based on these experimental data, because it is more convenient to use for designing a diver-tor.

Nomenclature

- Bo : $= q_{cr}/Gh_{fg}$, boiling number
 c_p : specific heat at constant pressure, J/kg K
 d : test tube inner diameter, m
 G : $= \rho_l u$, mass flux, kg/m²s
 g : acceleration of gravity, m/s²
 h_{fg} : latent heat of vaporization, J/kg
 L : heated length, m
 L_e : entrance length, m
 L_{ipt} : distance between inlet pressure transducer and inlet of the heated length, m
 P_{in} : pressure at inlet of heated length, kPa
 P_{ipt} : pressure measured by inlet pressure transducer, kPa
 P_{out} : pressure at outlet of heated length, kPa
 $(P_{out})_{cal}$: calculated outlet pressure, kPa
 P_{opt} : pressure measured by outlet pressure transducer, kPa
 Q_0 : initial exponential heat input, W/m²
 q : heat flux, W/m²
 $q_{cr,sub}$: critical heat flux for subcooled condition, W/m²
 Re : $= Gd/\mu_l$, Reynolds number
 Sc : $= c_{pl}(\Delta T_{sub,out})_{cal}/h_{fg} = c_{pl}\Delta T_{sub,out}/h_{fg}$, non-dimensional outlet subcooling
 Sc^* : $= c_{pl}\Delta T_{sub,in}/h_{fg}$, non-dimensional inlet subcooling
 t : time, s
 T_{in} : inlet liquid temperature, K
 T_{out} : outlet liquid temperature, K
 T_s : heater inner surface temperature, K
 $(T_{out})_{cal}$: calculated outlet liquid temperature, K
 T_{sat} : saturation temperature, K
 $T_{sat,out}$: outlet saturation temperature, K
 $\Delta T_{sub,in}$: $= (T_{sat} - T_{in})$, inlet liquid subcooling, K
 $\Delta T_{sub,out}$: $= (T_{sat} - T_{out})$, outlet liquid subcooling, K
 $(\Delta T_{sub,out})_{cal}$: calculated outlet liquid subcooling, K
 u : flow velocity, m/s
 We : $= G^2 d / \rho_l \sigma$, Weber number
 λ : friction factor for smooth tube
 ρ : density, kg/m³
 σ : surface tension, N/m
 τ : exponential period, s
- Superscript

cal : calculated

g : vapor

in : inlet

out : outlet

l : liquid

sat : saturated conditions

sub : subcooled conditions

wnh : with no heating

2. Experimental Apparatus and Method

The schematic diagram of experimental water loop 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 four test sections whose inner diameters are 3, 6, 9 and 12 mm. Test sections were vertically oriented with water flowing upward. Two test sections of the inner diameter of 3 and 6 mm were used in this work. The circulating water was distilled and deionized with about 5-M Ω 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 nitrogen gas. The pressure at the inlet of the test tube was controlled within ± 1 kPa of a desired value by using a pressure controller. The cross-sectional view of 3-mm inner diameter test section used in this work is typically shown in Fig. 2. The rough inner surface was fabricated by annealing the test tubes first in the air and was then acidized. The rough inner surface test tube was used as a standard one. The test tube was reinforced with the heat-shrink Teflon tube because the test tube wall was too thin for high pressure experiment. Wall thickness of the test tubes was 0.5 mm. The silver-coated 5-mm thickness copper-electrode-plates to supply heating current were soldered

Fig. 1 Schematic diagram of experimental apparatus

Fig. 3 $q_{cr,sub}$ vs. $\Delta T_{sub,out}$ for an inner diameter of 3 mm with a heated length of 33 mm at an outlet pressure of 800 kPa

Fig. 5 $q_{cr,sub}$ vs. $\Delta T_{sub,out}$ for an inner diameter of 3 mm with a heated length of 120 mm at an outlet pressure of 800 kPa

Fig. 4 $q_{cr,sub}$ vs. $\Delta T_{sub,out}$ for an inner diameter of 3 mm with a heated length of 67 mm at an outlet pressure of 800 kPa

Fig. 6 $q_{cr,sub}$ vs. $\Delta T_{sub,out}$ for an inner diameter of 3 mm with a heated length of 150 mm at an outlet pressure of 800 kPa

Inlet flow velocity (u) 4.0, 6.9, 9.9 and 13.3 m/s

Inlet Pressure (P_{in}) 753–995 kPa

Outlet Pressure (P_{out}) 720–887 kPa

Inlet Subcooling ($\Delta T_{sub,in}$) 48–148 K

Outlet Subcooling ($\Delta T_{sub,out}$) 10.5–95.1 K

Inlet Liquid Temperature 295–395 K

Steadily Increasing Heat Input $Q_0 \exp(t/\tau)$, $\tau = 10$, 20 and 33.3 s

3.2 CHF against outlet subcooling

The CHFs, $q_{cr,sub}$, for the inner diameter of 3 mm with $L = 33, 67, 120$ and 150 mm at the outlet pressure of around 800 kPa are shown versus the outlet subcoolings measured, $\Delta T_{sub,out}$, with the flow velocities of 4.0, 6.9, 9.9 and 13.3 m/s in Figs. 3 to 6, respectively. The outlet subcooling, $\Delta T_{sub,out}$, averaged over the cross sectional area was obtained from the measured outlet liquid temperature, T_{out} , and outlet pressure, P_{out} . The CHFs become higher with an increase in flow velocity at a fixed $\Delta T_{sub,out}$. These figures illustrate the trends in the variation of CHF with increasing outlet subcooling. The CHFs first decrease to the minimum CHF at the $\Delta T_{sub,out}$ of around 30 K, and then increase with an increase in $\Delta T_{sub,out}$. The increasing rate becomes lower for higher $\Delta T_{sub,out}$. These

trends have been already reported by Hata, et al.^{(1),(2)} on CHF data for the heated length of 50 mm with the inner diameters of 6, 9 and 12 mm.

It is assumed that, in the first low subcooling range, flushing-like phenomenon due to the vapor bubbles from inner side of a small diameter tube may be occurring and inducing the increase of flow velocity through the reduction in macroscopic density of two-phase mixture. The enhancement of CHF by this mechanism will become insignificant with the increase of subcooling. It is likely that the first low subcooling range would become narrower by using a larger diameter test tube. More detailed study on the CHF in the first low subcooling range for a vertical short tube will appear in the near future.

3.2.1 Influence of L/d Figures 7 to 10 show the influence of L/d on the CHF for inner diameters of 3, 6, 9 and 12 mm at $\Delta T_{sub,out}$ of 50, 70, 90 and 90 K respectively. The $q_{cr,sub}$ for the L/d ranging from 4.08 to 50 were shown versus the L/d with the flow velocity as a parameter. The CHFs become linearly lower with the increase in the L/d . The slope of each curve on the log-log graph is almost constant about -0.1 except that for the flow velocity of 4.0 m/s in Fig. 7, although it has been reported

Fig. 7 $q_{cr,sub}$ vs. L/d for an inner diameter of 3 mm at $\Delta T_{sub,out}$ of 50 K with the flow velocity of 4.0, 6.9, 9.9 and 13.3 m/s

Fig. 9 $q_{cr,sub}$ vs. L/d for an inner diameter of 9 mm at $\Delta T_{sub,out}$ of 90 K with the flow velocity of 4.0, 6.9, 9.9 and 13.3 m/s

Fig. 8 $q_{cr,sub}$ vs. L/d for an inner diameter of 6 mm at $\Delta T_{sub,out}$ of 70 K with the flow velocity of 4.0, 6.9, 9.9 and 13.3 m/s

Fig. 10 $q_{cr,sub}$ vs. L/d for an inner diameter of 12 mm at $\Delta T_{sub,out}$ of 90 K with the flow velocity of 4.0, 6.9, 9.9 and 13.3 m/s

that the CHFs are independent L/d of in the range of L/d larger than 40⁽⁶⁾. Furthermore, the slope for $u = 4.0$ m/s in the figure is about -0.25 . The trend of $(L/d)^{-0.25}$ dependence under this experimental condition can also be seen for the experimental data by Bergles⁽⁷⁾. It is supposed that the bubble boundary layer under subcooled condition become thicker along the heated length of the test tube and further, the thickness become especially larger in comparison with the vapor bubble diameter at low flow velocity with small tube inner diameter.

3.2.2 CHF correlation It has been clarified that the $q_{cr,sub}$ against $\Delta T_{sub,out}$ for a fixed L/d are almost proportional to $d^{-0.4}$, $u^{0.4}$ and $(\Delta T_{sub,out})^{0.7}$ for $\Delta T_{sub,out} \geq 30$ K. The CHF correlation against outlet subcooling, Eq. (1), has been derived⁽⁵⁾. In this work, the $q_{cr,sub}$ are also proportional to $(L/d)^{-0.1}$ except for the experimental data at $u = 4.0$ m/s for $d = 3$ mm, as mentioned above. The existing CHF correlation against outlet subcooling, Eq. (1), was modified to new one containing the L/d effect

as follows based on these experimental data for wide L/d range from 4.08 to 50 clarified in this work.

$$Bo = 0.082 \left\{ \frac{d}{\sqrt{\sigma/g(\rho_l - \rho_g)}} \right\}^{-0.1} We^{-0.3} \left(\frac{L}{d} \right)^{-0.1} Sc^{0.7} \quad (4)$$

for outlet subcooling ($\Delta T_{sub,out} \geq 30$ K)

where, Sc is non-dimensional outlet subcooling, $Sc = c_{pl}/\Delta T_{sub,out}/h_{fg}$. Saturated thermo-physical properties were evaluated at the outlet pressure.

The curves given by Eq. (4) at each flow velocity are shown in Figs. 3 to 10 for comparison. The CHF data for $\Delta T_{sub,out} \geq 30$ K are in good agreement with the values given by the correlation. Equation (4) was derived based on the experimental data at the outlet pressure of 800 kPa. Besides the experimental data obtained in this work, we have already reported the CHFs (1 611 points) for the wide range of $P_{out} = 159$ kPa to 1 MPa, $d = 3, 6, 9$ and 12 mm, $L = 33$ to 150 mm, $\Delta T_{sub,out} = -4$ to 130 K and $u = 4.0$ to 13.3 m/s⁽¹⁾⁻⁽⁵⁾. To confirm the applicability of

Fig. 11 Ratio of CHF data for the inner diameter of 3, 6, 9 and 12 mm to the values derived from the outlet CHF correlation versus $\Delta T_{sub,out}$ at outlet pressures of 159 kPa–1 MPa

Fig. 12 Comparison of the values derived from the outlet CHF correlation with other workers' CHF data

Eq. (4) to the data for wide range of pressures, the ratios of these CHF data to the corresponding values calculated by Eq. (4) are shown versus $\Delta T_{sub,out}$ in Fig. 11. Most of the data are within $\pm 15\%$ for $30 \text{ K} \leq \Delta T_{sub,out} \leq 140 \text{ K}$.

3.2.3 Comparison of our correlation with other workers' CHF data The values derived from the correlation against the outlet subcooling are compared with other workers' experimental data^{(7)–(9)} with d , P_{out} , $\Delta T_{sub,out}$ and G as a parameter in Fig. 12. The experimental data for $d = 1.07 \text{ mm}$ by Vandervort et al. are in good agreement with the values given by the correlation in the whole experimental range. Those for $d = 2$ and 3 mm by Nariai et al. show nearly the same trend of dependence on the values derived from the correlation, although the $q_{cr,sub}$ for $d = 1 \text{ mm}$ are proportional to $(L/d)^{-0.54}$ and the experimental data point for $L/d = 10$ is far higher than the value given by the correlation. Those by Bergles are 1.78 to 1.35 times as large as the correlation in the whole experimental range. And furthermore, it is confirmed that the decreasing rate of the $q_{cr,sub}$ is a little smaller than that for the correlation, as mentioned above.

Fig. 13 $q_{cr,sub}$ vs. $\Delta T_{sub,in}$ for an inner diameter of 3 mm with a heated length of 33 mm at inlet pressures of 818–973 kPa

Fig. 14 $q_{cr,sub}$ vs. $\Delta T_{sub,in}$ for an inner diameter of 3 mm with a heated length of 67 mm at inlet pressures of 819–927 kPa

3.3 CHF against inlet subcooling

Derivation of CHF correlation against inlet subcooling is useful to investigate the reliability of a divertor plate. Of course the relation between CHF and inlet subcooling can be implicitly obtained for a given value of L/d by solving the CHF correlation against outlet subcooling and the energy balance equation for the test tube. However explicit CHF correlation as a function of inlet subcooling is more convenient to use. We have given the CHF correlation against inlet subcooling.

The relation between $q_{cr,sub}$ and $\Delta T_{sub,out}$ shown in Figs. 3 to 6 are rewritten on $q_{cr,sub}$ vs. $\Delta T_{sub,in}$ graph in Figs. 13 to 16 to know the influence of $\Delta T_{sub,in}$ on CHF for flow velocities from 4.0 to 13.3 m/s. The inlet subcooling, $\Delta T_{sub,in}$, was obtained by the measured inlet liquid temperature, T_{in} , and inlet pressure, P_{in} . The CHF's first decrease to the minimum CHF at the $\Delta T_{sub,in}$ of around 50 K, and then increase with an increase in $\Delta T_{sub,in}$. The increasing rate becomes also lower for higher $\Delta T_{sub,in}$. The values of CHF data show nearly the same trends of dependence on $\Delta T_{sub,out}$, although the value of $\Delta T_{sub,in}$ at minimum CHF point is far higher than that of $\Delta T_{sub,out}$.

Fig. 15 $q_{cr,sub}$ vs. $\Delta T_{sub,in}$ for an inner diameter of 3 mm with a heated length of 120 mm at inlet pressures of 818–950 kPa

Fig. 16 $q_{cr,sub}$ vs. $\Delta T_{sub,in}$ for an inner diameter of 3 mm with a heated length of 150 mm at inlet pressures of 819–957 kPa

3.3.1 Influence of L/d Figures 17 to 20 show the influence of the L/d on the CHF for the inner diameter of 3, 6, 9 and 12 mm at fixed inlet subcooling of 130, 130, 135 and 110 K, respectively. The $q_{cr,sub}$ for the ranging from 4.08 to 50 were shown versus the L/d with the flow velocity as a parameter. As shown in Fig. 17, the values of q_{cr} for a fixed value of inlet subcooling and flow velocity become exponentially lower with the increase in L/d . As mentioned above the CHF against inlet subcooling can be implicitly obtained for a given value of L/d by solving the CHF correlation against outlet subcooling, Eq. (4), and the energy balance equation for the test tube given as,

$$\begin{aligned} \Delta T_{sub,out} &= T_{sub,out} - (T_{out})_{cal} \\ &= T_{sub,out} - \left(T_{in} + \frac{4Lq_{cr,sub}}{uc_p\rho_l d} \right) \end{aligned} \quad (5)$$

Thermo-physical properties were evaluated at the temperature of $\{T_{in} + (T_{out})_{cal}\}/2$. The values of q_{cr} obtained implicitly from Eqs. (4) and (5) are shown as each symbol in Figs. 17 to 20 for comparison. The CHF data for L/d ranging from 4.08 to 50 are in good agreement with the values obtained implicitly by these equations.

Fig. 17 $q_{cr,sub}$ vs. L/d for an inner diameter of 3 mm at $\Delta T_{sub,in}$ of 130 K with the flow velocity of 4.0, 6.9, 9.9 and 13.3 m/s

Fig. 18 $q_{cr,sub}$ vs. L/d for an inner diameter of 6 mm at $\Delta T_{sub,in}$ of 130 K with the flow velocity of 4.0, 6.9, 9.9 and 13.3 m/s

Fig. 19 $q_{cr,sub}$ vs. L/d for an inner diameter of 9 mm at $\Delta T_{sub,in}$ of 135 K with the flow velocity of 4.0, 6.9, 9.9 and 13.3 m/s

Fig. 20 $q_{cr,sub}$ vs. L/d for an inner diameter of 12 mm at $\Delta T_{sub,in}$ of 110 K with the flow velocity of 4.0, 6.9, 9.9 and 13.3 m/s

3.3.2 CHF correlation The CHF correlation against inlet subcooling for wide L/d range ($4.08 < L/d < 50$) is derived as follows based on the effects of L/d clarified in this work.

$$Bo = 0.082 \left\{ \frac{d}{\sqrt{\sigma/g(\rho_l - \rho_g)}} \right\}^{-0.1} \times We^{-0.3} \left(\frac{L}{d} \right)^{-0.1} e^{-\frac{(L/d)}{0.53Re^{0.4}}} Sc^{*0.7}$$

for inlet subcooling ($\Delta T_{sub,in} \geq 40$ K) (6)

where, Sc^* is non-dimensional inlet subcooling, $Sc^* = c_{pl}\Delta T_{sub,in}/h_{fg}$. Saturated thermo-physical properties were evaluated at the outlet pressure, $(P_{out})_{cal}$. The value of the $(P_{out})_{cal}$ is evaluated from the following equations⁽¹⁰⁾.

$$(P_{out})_{cal} = P_{ipt} - \lambda \frac{(L + L_{ipt})}{d} \frac{G^2}{2\rho_l} \quad (7)$$

$$\lambda = 4 \left(0.2295 + 0.6074 \frac{d}{L} \right) Re^{(-0.3305 - 0.02154 \frac{d}{L})} \quad (8)$$

where L_{ipt} is the distance between the inlet pressure transducer and the inlet of the heated length and λ is the friction factor for smooth tube.

The curves derived from Eq. (6) at each flow velocity are shown in Figs. 13 to 20 for comparison. The CHF data for $\Delta T_{sub,in} \geq 40$ K are in good agreement with the values given by the correlation. And further, this correlation can describe not only the CHF data obtained in this work for the inner diameter of 3 and 6 mm at the inlet pressure ranging from 753 to 995 kPa but also the authors' published CHF data (1 611 points) for the wide ranges of $P_{in} = 159$ kPa to 1 MPa, $d = 3$ to 12 mm, $L = 33$ to 150 mm, $\Delta T_{sub,in} = 10$ to 151 K and $u = 4.0$ to 13.3 m/s within 15% difference for $40 \text{ K} \leq \Delta T_{sub,in} \leq 150 \text{ K}$ as shown in Fig. 21.

3.3.3 Comparison of our correlation with other workers' CHF data The values derived from the correlation against the inlet subcooling are compared

Fig. 21 Ratio of CHF data for the inner diameter of 3, 6, 9 and 12 mm to the values derived from the inlet CHF correlation versus $\Delta T_{sub,in}$ at inlet pressures of 159 kPa–1 MPa

Fig. 22 Comparison of the values derived from the inlet CHF correlation with other workers' CHF data

with other workers' experimental data^{(11),(12)} with d , P_{out} , $\Delta T_{sub,in}$, G and u as a parameter in Fig. 22. The experimental data for $d = 8$ mm by Celata et al. agree well the values derived from the correlation. Those by Mudawar and Bowers show nearly the same trend of dependence on L/d , although those for only $P_{out} = 1.03$ MPa are about 20% lower than the correlation in this experimental range.

4. Conclusions

The critical heat fluxes (CHF) of subcooled water flow boiling are systematically measured for the inner-diameter ($d = 3$ and 6 mm) and the heated lengths ($L = 67, 120$ and 150 mm) with $L/d = 22$ to 50, the flow velocities ($u = 4.0$ to 13.3 m/s), the inlet subcoolings ($\Delta T_{sub,in} = 48$ to 148 K), the outlet subcoolings ($\Delta T_{sub,out} = 10.5$ to 95.1 K), the inlet pressure ($P_{in} = 753$ to 995 kPa) and the outlet pressure ($P_{out} = 720$ to 887 kPa). Experimental results lead to the following conclusions.

(1) The CHF first decrease to the minimum CHF

at $\Delta T_{sub,in}$ of around 50 K and $\Delta T_{sub,out}$ of around 30 K, and then increase with an increase in the subcooling. The increasing rate becomes lower for higher subcooling.

(2) The CHF becomes linearly lower with the increase in the L/d at a fixed d and $\Delta T_{sub,out}$. The slope on the log-log graph kept almost constant about -0.1 with the flow velocity ranging from 4.0 to 13.3 m/s except for the experimental data at $u = 4.0$ m/s for $d = 3$ mm.

(3) The existing CHF correlation against outlet subcooling was modified to new one containing the L/d effect based on these experimental data for wide L/d range from 4.08 to 50 clarified in this work.

(4) The CHF correlation against inlet subcooling for wide L/d range ($4.08 < L/d < 50$) is derived based on the effects of L/d clarified in this work to investigate the reliability of a divertor plate.

(5) The correlations against outlet and inlet subcooling can describe not only the CHF obtained in this work for the inner diameter of 3 and 6 mm at the outlet pressure of around 800 kPa but also the authors' published CHF data (1611 points) for the wide ranges of $P_{in} = 159$ kPa to 1 MPa, $d = 3$ to 12 mm, $L = 33$ to 150 mm and $u = 4.0$ to 13.3 m/s within 15% difference for $30 \text{ K} \leq \Delta T_{sub,out} \leq 140 \text{ K}$ and $40 \text{ K} \leq \Delta T_{sub,in} \leq 151 \text{ K}$.

Acknowledgements

This work was carried out by the LHD Joint Research Program of NIFS (National Institute for Fusion Science) Japan.

Appendix A: Entrance Length for Test Tube

For turbulence flow, the tube length in which the center line velocity reaches 99% of the maximum value is correlated by the following equation⁽¹³⁾.

$$\frac{L_e}{d} = 0.693 Re^{1/4} \quad (9)$$

where L_e is the entrance length.

Reynolds numbers, Re , for the test tube inner diameters ($d = 3$ to 12 mm) in this work and others⁽¹⁾⁻⁽⁵⁾ are given in the range of 4×10^4 to 10^6 with the flow velocities ($u = 4.0$ to 13.3 m/s) at the inlet pressures ($P_{in} = 159$ kPa to 1 MPa). The ratios of the entrance length to the test

tube inner diameter, L_e/d , are obtained ranging from 9.8 to 21.9 by Eq. (9).

The entrance lengths for 3, 6, 9 and 12-mm inner diameter test sections in the experimental water loop are shown in Table 1 respectively. The values of L_e/d for these test sections are enough larger than those calculated from Eq. (9), which are necessary to form fully developed flow profile.

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Table 1 Entrance lengths for 3, 6, 9 and 12 mm inner diameter test sections in the experimental water loop

$d(\text{mm})$	L_e	L_e/d
3	240	80
6	333	55.5
9	333	37
12	333	27.75

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