Experimental Thermal and Fluid Science 70 (2016) 255–269

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Mechanism of critical heat flux during flow boiling of subcooled water in a circular tube at high liquid Reynolds number ☆

Koichi Hata [a,*], Katsuya Fukuda [a], Suguru Masuzaki [b]

[a] Graduate School of Maritime Sciences, Kobe Univ., 5-1-1, Fukaeminami, Higashinada, Kobe 658-0022, Japan
[b] National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan

ARTICLE INFO

Article history:
Received 22 May 2015
Received in revised form 12 September 2015
Accepted 12 September 2015
Available online 16 September 2015

Keywords:
Mechanisms of subcooled flow boiling
Critical heat flux
Vertical circular tube
High liquid Reynolds number

ABSTRACT

The subcooled boiling heat transfer and the steady state critical heat flux (CHF) in a vertical circular tube for the liquid Reynolds numbers ($Re_d = 2.77 \times 10^4$–3.08×10^5) and the flow velocities (u = 3.95–30.80 m/s) are systematically measured by the experimental water loop comprised of a multistage canned-type circulation pump with high pump head. The SUS304 test tube of inner diameter (d = 6 mm) and heated length (L = 59.5 mm) is used in this work. The outer surface temperatures of the SUS304 test tube with heating are observed by an infrared thermal imaging camera and a video camera. The subcooled boiling heat transfers for SUS304 test tube are compared with the values calculated from correlations due to other researchers for the subcooled boiling heat transfer. The influence of flow velocity on the subcooled boiling heat transfer and the CHF is investigated in detail based on the experimental data. Nucleate boiling surface superheats at the CHF are close to the lower limit of the heterogeneous spontaneous nucleation temperature and the homogeneous spontaneous nucleation temperature. A suggestion as to what the dominant mechanism is for the subcooled flow boiling CHF on the SUS304 circular tube is made at high liquid Reynolds number. On the other hand, the RANS equations (Reynolds Averaged Navier–Stokes Simulation) with k–ε turbulent model in a circular tube of a 3 mm in diameter and a 526 mm long are numerically solved for heating of water on heated section of a 3 mm in diameter and a 67 mm long with various thicknesses of conductive sub-layer by using PHOENICS code under the same conditions as the experimental ones previously obtained and with temperature dependent thermo-physical fluid properties. The Platinum (Pt) test tube of inner diameter (d = 3 mm) and heated length (L = 66.5 mm) was used in this experiment. The thicknesses of conductive sub-layer from non-boiling regime to CHF are measured. The thicknesses of conductive sub-layer at the CHF point are predicted for various flow velocities. The experimental values of the CHF are also compared with the corresponding theoretical values of the liquid sub-layer dry-out models suggested by other researchers, respectively. A suggestion as to what the dominant mechanism is for the subcooled flow boiling CHF on the Pt circular tube is made at high liquid Reynolds number.

1. Introduction

The knowledge of subcooled boiling heat transfer at high liquid Reynolds number is important to discuss the mechanisms of subcooled flow boiling critical heat flux (CHF) in a vertical circular tube. Many researchers have experimentally studied the steady state CHFs uniformly heated on the normal tubes by a steadily increasing current for high liquid Reynolds number and given the correlations for calculating CHFs on the normal tubes. The authors have assumed that flow velocity will affect the incipient boiling superheat and the nucleate boiling heat transfer up to the CHF. Incipient boiling superheat may shift to a very high value at higher flow velocity and a direct transition to film boiling or a trend of a decrease in CHF with an increase in the flow velocity may occur due to the heterogeneous spontaneous nucleation. The accurate measurement for the subcooled boiling heat transfer up to the CHF is necessary to clarify a change in the mechanism of CHF.

The authors have systematically measured the subcooled boiling heat transfer and the steady state critical heat fluxes in a short vertical SUS304-tube for the flow velocities (u = 17.2–42.4 m/s), the inlet liquid temperatures (T_{in} = 293.3–362.5 K), the inlet pressures (P_{in} = 812.1–1467.9 kPa) and the exponentially increasing

☆ The 10th International Topical Meeting on Nuclear Thermal–Hydraulics, Operation and Safety (NUTHOS-10) NUTHOS10-1032 Okinawa, Japan, December 14–18, 2014.

* Corresponding author.
E-mail addresses: hatako1@people.kobe-u.ac.jp (K. Hata), fukuda@maritime.kobe-u.ac.jp (K. Fukuda), masuzaki@LHD.nifs.ac.jp (S. Masuzaki).

http://dx.doi.org/10.1016/j.expthermflusci.2015.09.015
0894-1777/

Nomenclature

Bo	q/Gh_{fg}, boiling number
Bo_{cr}	$q_{cr,sub,st}/Gh_{fg}$, boiling number at CHF point
d	test tube inner diameter, m
f_F	Fanning friction factor
G	$\rho_l u$, mass velocity, kg/m^2 s
h_{fg}	latent heat of vaporization, J/kg
L	heated length, m
L_{eff}	effective length, m
Nu_d	hd/λ_l, nusselt number
p	interval of L/d on which $q_{cr,sub,st}$ decreases by $1/e$-fold one
P_{in}	pressure at inlet of heated section, kPa
P_{ipt}	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
Pr	$c_p\mu/\lambda$, Prandtl number
Q	heat input per unit volume, W/m^3
Q_0	initial exponential heat input, W/m^3
q	heat flux, W/m^2
$q_{cr,sub,st}$	steady-state CHF for subcooled condition, W/m^2
R_a	average roughness, μm
Re_d	Gd/μ_l, Reynolds number
R_{max}	maximum roughness depth, μm
R_z	mean roughness depth, μm
r_i	test tube inner radius, m
r_o	test tube outer radius, m
$(\Delta r)_{out}$	outer control volume width for r-component, m
TEM	calculated temperature of the outer control volume, K
$\overline{T}$	average temperature of test tube, K
$T_{f,av}$	average liquid temperature, K
T_{in}	inlet liquid temperature, K
T_L	$(T_{in} + T_{out})/2$, liquid bulk mean temperature, K
T_{out}	outlet liquid temperature, K
$(T_{out})_{cal}$	calculated outlet liquid temperature, K
T_s	heater inner surface temperature, K
T_{sat}	saturation temperature, K
T_{so}	heater outer surface temperatures, K
$T_{s,av}$	average inner surface temperature, K
ΔT_L	$(T_{s,av} - T_L)$, temperature difference between average inner surface temperature and liquid bulk mean temperature, K
ΔT_{sat}	$T_s - T_{sat}$, inner surface superheat, K
$\Delta T_{sat,so}$	$T_s - T_{sat}$, outer surface superheat, K
u	flow velocity, m/s
y^+	$y(\tau_w\rho_l)^{0.5}/\nu_l$, dimensionless normal-distance coordinate
y^+_{CSL}	$(f_F/2)^{0.5}\rho_l u\delta_{CSL}/\mu_l$, non-dimensional thickness of conductive sub-layer
δ	conductive sub-layer on nucleate boiling heat transfer
δ_{CSL}	$(\Delta r)_{out}/2$, thickness of conductive sub-layer and conductive sub-layer on forced convection
ε	emissivity and rate of dissipation of turbulent energy, m^2/s^3
μ_l	viscosity, Ns/m^2
μ_w	viscosity at tube wall temperature, Ns/m^2
ν_l	μ_l/ρ_l, kinematic viscosity of fluid, Ns m/kg
ρ_l	density of fluid, kg/m^3
τ_w	shear stress at the wall, N/m^2

heat input ($Q = Q_0\ exp(t/\tau)$, $\tau = 8.5$ s) by the experimental water loop comprised of a multistage canned-type circulation pump with high pump head [1,2]. The SUS304 test tubes of inner diameters ($d = 3$ and 6 mm), heated lengths ($L = 33$ and 59.5 mm), effective lengths ($L_{eff} = 23.3$ and 49.1 mm), L/d (=11 and 9.92), L_{eff}/d (=7.77 and 8.18), and wall thickness ($\delta = 0.5$ mm) with average surface roughness ($Ra = 3.18$ μm) were used in this work.

Outlet subcooling:

$$Bo_{cr} = 0.082 D^{*-0.1}\ We^{-0.3}\left(\frac{L}{d}\right)^{-0.1} Sc^{0.7}$$
$$\text{for } \Delta T_{sub,out} \geqslant 30 \text{ K and } u \leqslant 13.3 \text{ m/s} \quad (1)$$

$$Bo_{cr} = 0.0523 D^{*-0.15}\ We^{-0.25}\left(\frac{L}{d}\right)^{-0.1} Sc^{0.7}$$
$$\text{for } \Delta T_{sub,out} \geqslant 30 \text{ K and } u > 13.3 \text{ m/s} \quad (2)$$

Inlet subcooling:

$$Bo_{cr} = C_1 D^{*-0.1} We^{-0.3}\left(\frac{L}{d}\right)^{-0.1} e^{-\frac{(L/d)}{C_2 Re_d^{0.4}}} Sc^{*C_3}$$
$$\text{for } \Delta T_{sub,in} \geqslant 40 \text{ K and } u \leqslant 13.3 \text{ m/s} \quad (3)$$

$$Bo_{cr} = C_4 D^{*-0.15} We^{-0.25}\left(\frac{L}{d}\right)^{-0.1} e^{-\frac{(L/d)}{C_5 Re_d^{0.5}}} Sc^{*C_6}$$
$$\text{for } \Delta T_{sub,in} \geqslant 40 \text{ K and u} > 13.3 \text{ m/s} \quad (4)$$

where $C_1 = 0.082$, $C_2 = 0.53$ and $C_3 = 0.7$ for $L/d \leqslant$ around 40 and $C_1 = 0.092$, $C_2 = 0.85$ and $C_3 = 0.9$ for $L/d >$ around 40. $C_4 = 0.0523$, $C_5 = 0.144$ and $C_6 = 0.7$ for $L/d \leqslant$ around 40 and $C_4 = 0.0587$, $C_5 = 0.231$ and $C_6 = 0.9$ for $L/d >$ around 40. Details of the influence of L/d are shown in Appendix A.1 [3]. Bo_{cr}, D^*, We, Sc and Sc^* are boiling number ($=q_{cr,sub}/Gh_{fg}$), non-dimensional diameter [$D^* = d/\{\sigma/g/(\rho_l - \rho_g)\}^{0.5}$], Weber number ($=G^2 d/\rho_l\sigma$), non-dimensional outlet subcooling ($=c_{pl}\Delta T_{sub,out}/h_{fg}$) and non-dimensional inlet subcooling ($Sc^* = c_{pl}\Delta T_{sub,in}/h_{fg}$), respectively. Saturated thermo-physical properties were evaluated at the outlet pressure. Most of the data for the exponentially increasing heat input ($Q_0\ exp(t/\tau)$, $\tau = 8.5$–33.3 s, 3323 points) are within ±15% differences of Eqs. (1)–(4) for the flow velocities, u, ranging from 4.0 to 42.4 m/s, respectively.

The inner surface temperature and the heat flux for different flow regimes ranging from single-phase flow heat transfer to CHF were explored. The subcooled boiling heat transfers for SUS304 test tube were compared with authors' Platinum test tube data [4] and the values calculated from correlations due to other researchers for the subcooled boiling heat transfer. The influence of flow velocity on the subcooled boiling heat transfer and the CHF was investigated in detail. And the correlation of the subcooled boiling heat transfer for turbulent flow of water in a short vertical SUS304-tube was given based on the experimental data. The precision or accuracy of a more wide set of correlation in predicting the set of data was evaluated [1,2]. The correlation can describe the subcooled boiling heat transfer coefficients obtained in this work within ±15% differences. Nucleate boiling surface superheats for the SUS304 test tube become very high. Those at the high flow velocity are close to the lower limit of Heterogeneous Spontaneous Nucleation Temperature [5]. The dominant mechanisms of the flow boiling CHF in a short vertical SUS304-tube were discussed. The CHF occur due to the hydro-dynamic instability suggested by Kutateladze [6] and Zuber [7] or due to the Heterogeneous Spontaneous Nucleation at the lower limit of Heterogeneous Spontaneous Nucleation Temperature.

The objectives of present study are fourfold. First is to measure the subcooled boiling heat transfer and the steady state CHFs for a SUS304-circular test tube with a wide range of inlet subcoolings ($\Delta T_{sub,in}$) and flow velocities (u) at high liquid Reynolds number,