Experimental Thermal and Fluid Science 66 (2015) 160–172

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Transient critical heat fluxes of subcooled water flow boiling in a SUS304-circular tube caused by a rapid decrease in velocity from non-boiling regime

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ARTICLE INFO

Article history:
Received 1 November 2014
Received in revised form 11 March 2015
Accepted 20 March 2015
Available online 1 April 2015

Keywords:
Transient critical heat flux
Subcooled water flow boiling
SUS304-circular tube
Rapid decrease in velocity
Deceleration
Non-boiling regime

ABSTRACT

The flow transient critical heat fluxes (FT-CHFs, $q_{cr,sub}$) in a SUS304-circular tube caused by a rapid decrease in velocity from non-boiling regime are systematically measured for various initial flow velocities, initial heat fluxes, inlet liquid temperatures, outlet pressures and decelerations caused by a rapid decrease in velocity by the experimental water loop comprised of a multistage canned-type circulation pump controlled by an inverter. The SUS304-circular tubes of inner diameter (d = 6 mm), heated length (L = 59.5 mm), L/d (=9.92) and wall thickness (δ = 0.5 mm) with average surface roughness (Ra = 3.89 μm) are used in this work. The flow transient CHFs for SUS304-circular tube are compared with authors' steady-state CHF data for the empty VERTICAL and HORIZONTAL SUS304-circular tubes and the values calculated by authors' steady-state CHF correlations against outlet and inlet subcoolings for the empty circular tube. The influences of initial flow velocity (u_0), initial heat flux (q_0) and deceleration caused by a rapid decrease in velocity (α) on the flow transient CHF are investigated into details and the widely and precisely predictable correlations of CHF and flow velocity at the flow transient CHF for the circular tube is given based on the experimental data. The correlations can describe the flow velocity and the CHFs at the flow transient CHFs for SUS304-circular tube obtained in this work within ± 20% difference.

1. Introduction

Flow transient critical heat fluxes of subcooled water flow boiling in a SUS304-circular tube caused by a rapid decrease in velocity from non-boiling regime is necessary to investigate the reliability of a divertor in a nuclear fusion facility at a loss of flow accident. The nuclear fusion facility has two operation modes. One is the steady-state operation mode, and the other is the transient one. The plasma facing material in transient operation mode is exposed to a heat load three times larger or more than during steady-state operation for several seconds. The knowledge of high heat flux heat removal during various decelerations caused by the rapid decreases in velocity (flow transients) becomes especially very important to take the heat out of the plasma facing material for short pulse high heat flux test mode. The influence of deceleration caused by a rapid decrease in velocity on transient CHF in subcooled water flow will be immediately supposed to be applied to thermal analysis of the divertor of a helical type fusion experimental device which is Large Helical Device (LHD) located in National Institute for Fusion Science (NIFS), Japan.

Many researchers have experimentally studied the steady state CHFs uniformly heated on the circular tube with and without twisted-tape insert by a steadily increasing current at a fixed mass velocity for Fusion Reactor Safety (FRS), shown that the circular tube with twisted-tape insert provide considerable enhancement of CHFs in subcooled flow boiling and given the correlations for calculating CHFs on the circular tube with twisted-tape insert [1–9]. We have supposed that the enhancement of CHFs for the circular tube with twisted-tape insert will be due to reduction of conductive sub-layer thickness on heated surface of test tube and due to an increase in liquid flow velocity from straight flow to swirl one, not new mechanism of heat transfer crisis. And furthermore, we have also supposed 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

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http://dx.doi.org/10.1016/j.expthermflusci.2015.03.014
0894-1777/

Nomenclature

a, b, c	fitted constant
Bo_{cr}	$q_{cr,sub}/Gh_{fg}$, boiling number
$Bo_{cr,sw}$	$= \frac{q_{cr,sub,st}}{Gh_{fg}} \times \frac{(\pi d^2 - 4w\delta_T)}{\pi d^2} \times \frac{2y}{(4y^2+2\pi^2)^{0.5}}$, boiling number based on swirl velocity
C	constant in Eq. (11)
C_1, C_2, C_3	constants in Eqs. (1) and (22)
c_p	specific heat at constant pressure (J/kg K)
D^*	$d/\{\sigma/g/(\rho_l - \rho_g)\}^{0.5}$, non-dimensional diameter
d	test tube inner diameter (m)
f_{pi}	pump input frequency (Hz)
f_{pi0}	initial pump input frequency (Hz)
G	$\rho_l u$, mass velocity (kg/m^2 s)
g	acceleration of gravity (m/s^2)
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_{eff}	effective length (m)
L_{ipt}	distance between inlet pressure transducer and inlet of the heated section (m)
L_{opt}	distance between outlet pressure transducer and outlet of the heated section (m)
P	pressure (kPa)
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_{out0}	initial outlet pressure (kPa)
P_{opt}	pressure measured by outlet pressure transducer (kPa)
p^*	$=\tau u/\{\sigma/g/(\rho_l - \rho_g)\}^{0.5}$, non-dimensional exponential period
Q	heat generation rate and heat input per unit volume (W/m^3)
Q_0	initial exponential heat input (W/m^3)
q	heat flux (W/m^2)
q_0	initial heat flux (W/m^2)
$q_{cr,sub}$	flow transient CHF (W/m^2)
$q_{cr,sub,st}$	steady-state CHF for subcooled condition (W/m^2)
R_1 to R_3	resistance in a double bridge circuit (Ω)
Ra	average roughness (μm)
$Rmax$	maximum roughness depth (μm)
Rz	mean roughness depth (μm)
r	radius (m)
r_i	test tube inner radius (m)
r_o	test tube outer radius (m)
S	surface area (m^2)
Sc	$= c_{pl}\Delta T_{sub,out}/h_{fg}$, non-dimensional outlet subcooling
Sc^*	$= c_{pl}\Delta T_{sub,in}/h_{fg}$, non-dimensional inlet subcooling
T	temperature of the test tube (K)
$\overline{T}$	average temperature of the test tube (K)
T_H	homogeneous spontaneous nucleation temperature (K)
T_{HET}	lower limit of heterogeneous spontaneous nucleation temperature (K)
T_{in}	inlet liquid temperature (K)
T_{out}	outlet liquid temperature (K)
T_s	heater inner surface temperature (K)
t	time (s)
t_d	deceleration time setting (s)
$\Delta T_{sub,in}$	$= (T_{sat} - T_{in})$, inlet subcooling (K)
$\Delta T_{sub,in0}$	initial inlet subcooling (K)
$\Delta T_{sub,out}$	$(T_{sat} - T_{out})$, outlet subcooling (K)
u	inlet flow velocity (m/s)
u_0	initial flow velocity (m/s)
u_{cr}	flow velocity at the flow transient CHF (m/s)
V	volume (m^3)
V_I	voltage drop across standard resistance (V)
V_R	voltage drop across two potential taps (V)
V_{R1}	voltage drop across two electrodes (V)
V_T	unbalance voltage in a double bridge circuit (V)
We	$= G^2 d/\rho_l \sigma$, Weber number
We_{sw}	$= \frac{G^2 d}{\rho_l \sigma} \times \left(\frac{\pi d^2}{\pi d^2 - 4w\delta_T}\right)^2 \times \left[\frac{(4y^2+2\pi^2)^{0.5}}{2y}\right]^2$, Weber number based on swirl velocity
w	width of twisted-tape (m)
y	$= H/d$ = (pitch of 180° rotation)/d, twist ratio of twisted-tape
α	deceleration caused by a rapid decrease in velocity (m/s^2)
δ	wall thickness (mm)
δ_T	thickness of twisted-tape (m)
λ	thermal conductivity (W/m K)
μ	viscosity (Ns/m^2)
ρ	density (kg/m^3)
σ	surface tension (N/m)
τ	exponential period (s)

Subscript

cr	critical
g	vapor
in	inlet
out	outlet
l	liquid
sat	saturated condition
sub	subcooled condition
wnh	with no heating

trend of a decrease in CHF with a delay of boiling initiation may occur due to the heterogeneous spontaneous nucleation but not due to the hydro-dynamic instability. The accurate measurement for the subcooled boiling heat transfer up to the CHF is necessary to clarify a change in the mechanism of CHF.

Recently, we systematically measured the power transient critical heat fluxes (PT-CHFs) of subcooled water flow boiling in a SUS304-circular tube for the inner diameter (d = 6 mm), the heated length (L = 59.4 mm), the effective length (L_{eff} = 49.4 mm), L/d (=9.9), L_{eff}/d (=8.23) and the wall thickness (δ = 0.5 mm) with the twisted-tape of width (w = 5.6 mm), thickness (δ_T = 0.6 mm), total length (l = 372 mm) and twist ratios, y [H/d = (pitch of 180° rotation)/d], of 2.40, 3.37 and 4.45 for the mass velocities (G = 3988–13,620 kg/m^2 s), the inlet liquid temperatures (T_{in} = 287.55–313.14 K), the outlet pressures (P_{out} = 805.11–870.23 kPa) and the exponentially increasing heat inputs ($Q = Q_0 exp(t/\tau)$, τ = 26.85 ms to 8.43 s). The influences of twisted-tape insert, twist ratio, heating rate and swirl velocity on the transient CHF are investigated into details. And the power transient CHF correlations against inlet and outlet subcoolings for the test tubes with twisted-tape insert are derived due to the effect of boiling number based on swirl velocity, $Bo_{cr,sw}$, and Weber number based on swirl velocity, We_{sw} [10–13].

$$Bo_{cr,sw} = C_1 D^{*-0.1} We_{sw}^{-0.3} \left(\frac{L}{d}\right)^{-0.1} e^{-\frac{(L/d)}{C_2\, Re_d^{0.4}}} Sc^{*C_3} \times (1 + 11.4p^{*-0.6})$$
$$\text{if inlet subcooling is known } (\Delta T_{sub,in} \geq 40\ \text{K}) \quad (1)$$