International Communications in Heat and Mass Transfer 82 (2017) 74–80

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Correlation of high critical heat flux during flow boiling for water in a small tube at various subcooled conditions

M. Shibahara *, K. Fukuda, Q.S. Liu, K. Hata

Graduate School of Maritime Sciences, Kobe University, 5-1-1, Fukaeminami, Higashinada, Kobe, Hyogo 658-0022, Japan

ARTICLE INFO

Available online xxxx

Keyword:
Flow boiling
CHF
Subcooled boiling of water
Small tube

ABSTRACT

High critical heat fluxes (CHFs) for subcooled boiling of water in a small tube were investigated experimentally. A platinum tube with an inner diameter of 1.0 mm and a length of 40.9 mm was used in the experiment. The upward flow velocity, the subcooling of water, and the outlet pressure of the experimental tube were varied to enable a parametric study of the CHFs. The flow velocity ranged from 9 to 13 m/s and the inlet subcooling ranged from 69 to 148 K. The boiling number decreased with increasing Weber number. The boiling number is also dependent on a non-dimensional parameter and the density ratio of liquid to vapor. A correlation for the high CHF of the small tube was obtained based on the experimental data. Finally, the high CHF correlation was evaluated using the CHF data obtained by other researchers.

1. Introduction

Subcooled water is used to reduce the heat load in various high heat flux applications such as in the divertor in fusion reactors, electric devices, and hybrid/electric/fuel cell vehicles [1]. Since the power densities of these devices have been increasing, heat removal technology for high heat fluxes in small tubes is an increasingly interesting research topic. In particular, experimental data from research on critical heat fluxes (CHFs) are important for understanding the limit of cooling [2].

Experimental data on CHFs for small tubes were reported by Bergles [3]. Nariai et al. [4] obtained CHFs for subcooled water in small stainless steel tubes under atmospheric pressure. They also modified Tong's correlation [5] since the predicted CHF value was higher than that of their experiment at the low subcooling. Celata et al. [6–8] obtained experimental data for miniature stainless steel tubes and proposed correlations for the CHFs. They classified the CHFs using thermal equilibrium qualities. Vandervort et al. [9] carried out an experiment on the CHF and demonstrated that the CHF for a small stainless steel tube increases as the inner diameter of tube decreases for diameters ≤ 3 mm. They also showed experimental data on premature failures of the CHFs.

Mudawar and Bowers [10] measured ultra-high CHFs using small tubes that were made of either SUS304 or Cu-Ni 30%. They showed that the flow regime at high flow velocities was different from the flow regime under low flow velocity conditions, and that the CHFs increased with decreasing tube inner diameter. Furthermore, Hall and Mudawar [11] obtained a correlation for ultra-high CHFs based on their experimental data and compared it to other correlations. In their experimental range, the outlet subcoolings were high because the ratio of the length to diameter was small.

Hata and Noda [12], Hata and Masuzaki [13], and Hata et al. [14] carried out steady state and transient experiments for subcooled boiling of water flowing upward in short conventional tubes mounted vertically in the water loop apparatus. They clarified the effect of the tube material, inlet and outlet subcooling, ratio of length to diameter, e-folding time, and flow velocities on the CHFs given exponentially increasing heat inputs under a wide range of experimental conditions. Although they conducted a parametric study of steady state and transient CHFs in conventional tubes, their findings did not cover the mini and microscales, and there were no correlations in the mini and micro scale channels.

Shibahara et al. [15] measured steady and transient CHFs for a stainless tube with the inner diameter of 1.0 mm and compared the experimental data with some CHF models [16–18]. Although the CHF data in steady state were in good agreement with the predicted values of the CHF models at the high subcooling, the measured CHF values were higher than those of the CHF models at the low subcooling.

In this study, the CHFs for subcooled boiling of water flowing in a small platinum tube were measured at various inlet subcooling conditions and flow velocities to obtain experimental data under low outlet subcooling conditions. The aim of this study is to clarify the effect of the Weber number, subcooling, and the density ratio of liquid to vapor on the boiling number, and to suggest a new CHF correlation in small tubes.

---

* Corresponding author.
E-mail address: sibahara@maritime.kobe-u.ac.jp (M. Shibahara).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.02.012
0735-1933/

Nomenclature

A	surface area, m^2
B	basis limit, (−)
Bo	$=q_{cr}/Gh_{fg}$, boiling number, (−)
c	specific heat, J/kg K
c_p	specific heat at constant pressure, J/kg K
d	inner diameter of the experimental tube, m
d_o	outer diameter of the experimental tube, m
D^*	$=d/\{\sigma/g(\rho_l-\rho_g)\}^{0.5}$, non-dimensional diameter, (−)
G	mass velocity, kg/m^2s
g	acceleration of gravity, m/s^2
h_{fg}	latent heat of vaporization, J/kg
I	current through the experimental tube, A
L	heated length, m
L_{ipt}	length from the inlet of the experimental tube to the inlet pressure gauge (=0.053), m
L_{opt}	length from the outlet of the experimental tube to the outlet pressure gauge (=0.053), m
P	pressure, kPa
Q	heat transfer rate, W
Q_0	initial exponential heat input, W/m^3
Q_{CHF}	heat transfer rate at CHF point, W
$\dot{Q}$	heat input per unit volume, W/m^3
q	heat flux, W/m^2
q_{cr}	critical heat flux, W/m^2
R_0	electrical resistance at 0 °C, Ω
R_1, R_2, R_3	electrical resistance of double bridge circuit, Ω
R_a	average roughness, μm
R_s	standard resistor, Ω
R_T	electrical resistance of the experimental tube, Ω
R_y	maximum roughness depth, μm
R_z	mean roughness depth, μm
r	radius of the experimental tube, m
r_x	lead resistance, Ω
S	precision index, (−)
Sc	$=c_{pl}\Delta T_{sub,out}/h_{fg}$, non-dimensional outlet subcooling, (−)
Sp	$=\rho_l c_{pl}\Delta T_{sub,out}/\rho_g h_{fg}$, non-dimensional parameter, (−)
T	temperature, K
T_a	$=\int_{r_i}^{r_o}2\pi rT(r)dr/\pi(r_o^2-r_i^2)$, average temperature of the experimental tube, K
t	time, s
t_{95}	confidence level, (−)
t_{CHF}	elapsed time at CHF point, s
ΔT_{sat}	$=T_s - T_{sat}$, surface superheat, 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
U	uncertainty, (−)
u	flow velocity, m/s
V	volume of the experimental tube, m^3
V_I	voltage of the standard resistor, V
V_R	voltage of the experimental tube, V
V_T	unbalanced voltage, V
We	$=G^2d/\rho_l\sigma$, Weber number, (−)

Greek symbols

α	coefficient of R_T, (−)
β	coefficient of R_T, (−)
ε	emissivity, (−)
λ	thermal conductivity, W/mK
ρ	density, kg/m^3
σ	surface tension, N/m
σ_{sb}	Stefan-Boltzmann constant ($=5.67\times10^{-8}$), $W/m^2\,K^4$
τ	$=\int_0^t Q(t)dt/Q(t)$, e-folding time, s

Subscripts

exp	experimental value
g	vapor
h	heater
i	inner
in	inlet
l	liquid
o	outer
out	outlet
pred	predicted value
rad	radiation
RSS	root sum square
s	surface
sat	saturated condition
sub	subcooled condition
sur	surroundings
tot	total

2. Experimental setup and method

2.1. Experimental setup

The experimental apparatus consists of a pressurizer, a condenser, a cooler, a canned-type pump, a preheater, a flow sensor, an ion exchanger, and a test section (Fig. 1). An experimental tube made of platinum is mounted vertically in the water loop. The water loop is made of stainless steel (SUS304) and is capable of pressurization up to 2 MPa.

Fig. 2 shows a vertical cross-sectional view of the test section. The inner diameter of the platinum tube is 1.0 mm and the thickness is 0.4 mm. The heated length of the experimental tube, L, is 40.9 mm. Both ends of the experimental tube were soldered to 5.0 mm thick silver-coated copper plates that served as electrodes.

2.2. Experimental method

The experiment was conducted as follows: firstly, subcooled water was circulated for deionization to a specific resistivity of approximately 2.0×10^{-7} S/cm by the ion exchanger for at least 30 min. To reduce the influence of non-condensable gases, a boiling process for degassing the deionized subcooled water was carried out. Then, the deionized water in the pressurizer was pressurized by saturated vapor to between 200 and 900 kPa and controlled to within ±1 kPa using the heater controller. The subcooled water was cooled by the cooler and was then heated to the desired temperature level by the preheater. The flow velocity was controlled by regulating the frequency of the three-phase alternating power source to the pump. After the liquid temperature and flow velocity were confirmed to be stable in the water loop, an electric current was supplied to the experimental tube with an exponential function as follows:

$$\dot{Q}(t)=Q_0\exp(t/\tau). \tag{1}$$

Since the heat input can be controlled by a long e-folding time, which ranged from 9.2 to 18.3 s, the heat transfer process can be assumed to be in steady state.

2.3. Measurement method

Fig. 3 shows a double bridge circuit that includes the experimental tube as one of the branches. The experimental tube was heated by Joule heating, $Q=V_RI$, where V_R and I are the voltage of the experimental tube and the direct current in the electric circuit obtained by Ohm's law. Thus, $I=V_I\,/\,R_s$, where V_I and R_s are the voltage of the standard