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Research Paper

Boiling incipience of subcooled water flowing in a narrow tube using wavelet analysis

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HIGHLIGHTS

- Incipient boiling phenomena of subcooled water in a narrow tube were observed.
- The boiling signal was analyzed by the wavelet decomposition method.
- The semi-empirical correlation of the boiling incipience was obtained.

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ABSTRACT

Various incipient boiling phenomena for subcooled water flowing in a uniformly heated narrow tube were observed experimentally. The boiling signal was analyzed using the wavelet decomposition method. The boiling incipience of subcooled water in the narrow tube was recorded by a sound level meter at various flow velocities. A platinum tube was used as the experimental tube with an inner diameter of 1.0 mm. The length of the experimental tube was 23.2 mm. The tube was heated by the Joule effect using a direct current. The inlet temperature and flow velocities ranged 285–346 K and 2.5–14 m/s, respectively. The surface superheat ascended with an increase of the heat flux until the incipient boiling point was reached. The initial temperature overshoot did not appear as the outlet pressure increased. Since the existing correlations underestimated the incipient heat flux, a semi-empirical correlation of the boiling incipience was obtained based on the experimental data. The predicted value of the new correlation is in agreement with the experimental data within ±30%.

1. Introduction

Understanding of the boiling incipience in tubes is important for the safety assessment of industrial applications, since subcooled liquid is used in various fields, such as plasma facing components (PFC) in fusion reactors, rocket engines, and hydrogen storage that utilize narrow channels [1]. The liquid channel cooling is also used in insulated gate bipolar transistor (IGBT) modules that are used in hybrid vehicles, electric vehicles, and electric propulsion ships [2]. With the increase in the IGBT power density, dynamic cooling technology is required and the detection of the boiling incipience is more important for the safe operation of these power electronics. Furthermore, the knowledge of boiling incipience is necessary to design the divertor of the PFC. Since the edge localized mode incurs high heat flux at the divertor [3], the prediction of the boiling incipience in a cooling tube is an issue to be considered in the thermal design of the PFC.

Since their convective heat transfer coefficients are higher than those of gases, the convective heat transfer of various liquids was investigated experimentally and empirical correlations have been suggested [4–6]. For mini- and micro-channels, many studies of heat transfer characteristics have been conducted over the past decade [7]. Even though micro channels are known to enhance the heat transfer coefficient, the boiling incipience has not been clearly investigated so far. For conventional tubes up to an inner diameter of 2.0 mm, the boiling incipience can be predicted by the Bergles and Rohsenow [8] or Sato and Matsumura [9] correlations. In contrast, Ghiaasiaan and Chedester [10] mentioned that the predictions calculated by the correlations in [8] or [9] were lower than the results of Ghiaasiaan and Chedester's [10] and Inasaka et al.'s [11] experiments. Since the accuracy of these correlations is not satisfactory for micro scale phenomena, Ghiaasiaan and Chedester suggested the use of a new correlation modified by Davis and Anderson's model [12] using a ratio of thermocapillary

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Nomenclature

A	inner surface area of the experimental tube, m^2
a_j	approximation coefficient at the decomposition level of j (–)
b	systematic standard uncertainty (–)
C	coefficient in Eqs. (23), (24) and (31)
c	constant in Eq. (13)
c_h	specific heat of the platinum tube, J/kg K
c_p	specific heat at constant pressure, J/kg K
d	inner diameter, m
d_j	detail coefficient at the decomposition level of j (–)
f	boiling signal (–)
fs	frequency, Hz
h	heat transfer coefficient, (W/m^2 K)
h_{fg}	latent heat of vaporization, J/kg
I	direct current, A
J	maximum decomposition level of signal (–)
k	coverage factor (=2) (–)
L	length, m
MAE	mean absolute error,%
n	number of experimental data (–)
Nu	$=hd/\lambda$, Nusselt number (–)
P	pressure, kPa
Pr	$=\mu c_p/\lambda$, Prandtl number (–)
P_{cr}	critical pressure, kPa
P_{re}	$=P_{out}/P_{cr}$, reduced pressure, kPa
Q	heat transfer rate, W
Q_i	heat transfer rate at the boiling incipience, W
Q_0	initial exponential heat input, W/m^3
$\dot{Q}$	heat generation rate, W/m^3
q	heat flux, W/m^2
q_i	incipient heat flux, W/m^2
Re	$=\rho ud/\mu$, Reynolds number (–)
R_0	electrical resistance at 0 °C (=1.38 × 10^{-3}), Ω
R	electrical resistance, Ω
R^*	critical cavity radius
R_B	Bubble radius, m
R_a	average roughness, μm
R_s	standard resistor, Ω
R_T	electrical resistance of the experimental tube, Ω
R_y	maximum height, μm
R_z	ten-spot average roughness, μm
r	radius, m
r_x	lead resistance, Ω
s	random standard uncertainty of the mean of N measurements (–)
T	temperature, K
T_a	average temperature, K
T_i	incipient surface temperature, K
t	time, s
t_{95}	student's t value at a specified confidence level with v degrees of freedom (–)
ΔT_{sat}	$=T_s - T_{sat}$, surface superheat, K
$\Delta T_{sub,in}$	$=T_{sat} - T_{in}$, inlet liquid subcooling, K
U	expanded uncertainty
u	flow velocity, m/s
V	volume, m^3
V_I	voltage of the standard resistor, V
V_R	voltage of the experimental tube, V
V_T	unbalanced voltage, V
v	specific volume, m^3/kg
w	weighting factor
X	Fourier transform
y	distance from the wall, m

Greek symbols

α	coefficient of R_T (3.78 × 10^{-3}) (–)
β	coefficient of R_T (5.88 × 10^{-7}) (–)
ε	emissivity of platinum (–)
ϕ	scaling function (–)
λ	thermal conductivity, W/mK
μ	viscosity, Ns/m^2
v	number of degrees of freedom (–)
ρ	density, kg/m^3
σ	surface tension, N/m
σ_{sf}	Stefan-Bolzmann constant (=5.67 × 10^{-8} W/m^2 K^4) (–)
τ	$=\int_0^t Q(t)dt/Q(t)$, e-folding time, s
ψ	wavelet (–)
ζ	ratio of thermocapillary forces and aerodynamic forces in Eq. (25) (–)
ω	frequency response, dB

Subscripts

exp	experimental value
B	bubble
BR	Bergles and Rohsenow
GC	Ghiaasiaan and Chedester
f	liquid
g	vapor
h	heater
i	inner
in	inlet
MIC	microphone
o	outer
out	outlet
pred	predicted value
s	surface
sat	saturation
SLM	sound level meter
sur	surrounding
SM	Sato and Matsumura
sub	subcooling
w	wall
WSE	windscreen effect
WSC	windscreen correction

and aerodynamic forces. However, there is a limitation on the applicability of the model due to experimental restrictions.

Other investigators studied the heat transfer characteristics, including the critical heat flux (CHF) for water, using small platinum tubes and obtained the correlations of forced convection in the tubes at various experimental conditions [13–15]. However, the boiling incipience was not clarified because the pump noise was too high at high flow velocities.

To obtain a high accuracy correlation of boiling incipience in narrow tubes, this study focuses on the measurement of the boiling incipience using the wavelet decomposition method (WDM) [16]. Various incipient boiling phenomena for subcooled water flowing in a uniformly heated narrow tube were observed and the boiling signal was analyzed using WDM. Based on the experimental data and their analysis, an empirical correlation of the boiling incipience was obtained.