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Experimental investigations on bubble departure diameter and frequency of methane saturated nucleate pool boiling at four different pressures

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ABSTRACT

In this work, bubble departure diameters and bubble departure frequencies on saturated nucleate pool boiling of methane were studied. The experiments were conducted on the upper surface of a smooth vertical copper cylinder, at pressures of 0.15 MPa, 0.2 MPa, 0.3 MPa and 0.4 MPa with heat fluxes varying from 10.64 kW m^{-2} to 79.25 kW m^{-2}. Bubble departure diameters were measured from the images captured by a high-speed digital camera at lower heat fluxes less than 79.25 kW m^{-2}, at which isolated bubbles were obtained. Bubble departure frequencies were calculated by counting the numbers of the detachment bubbles and the corresponding time intervals. Their relationship with Jacob number (Ja) was analyzed. With an increase in Ja at a given pressure, bubble departure diameter increases while bubble departure frequency tends to decrease. After the comparisons with six most used correlations for bubble departure diameter, a new correlation was developed within ±20% deviation from most of the experimental data. Additionally, a new correlation for the relationship between bubble departure diameter and departure frequency was also proposed within ±20% deviation from most of the experimental fD_d^2.

1. Introduction

Nucleate boiling has raised wide attention in the world because of its considerable capacity to carry heat from a heater to a liquid, which also makes it an important process in refrigeration and other industrial applications. During nucleate boiling, a bubble nucleates and grows from a single site on the heated surface. When it grows to a certain size, it will depart from the surface into the liquid as a result of the joint effects of various forces, such as surface tension force, buoyancy force, inertia force and so on. It is supposed that bubble detachment on the heated surface is directly related to the boiling heat transfer. Due to the importance of the bubble departure process, bubble departure diameter has been shown to be one of the most important parameters in the heat transfer analysis. Bubble departure frequency, as another important parameter, usually correlates with bubble departure diameter. Extensive research has been conducted for nearly eighty years, and the most used correlations for them are summarized in Tables 1 and 2.

For bubble departure diameter, the correlations can be grouped into two types. One incorporates the term of $\{\sigma/[g(\rho_l-\rho_v)]\}^{1/2}$, the other doesn't.

The correlations of the first type have tried to relate Bond number to the effects of liquid properties, pressure, superheat or Ja number, heat flux, as well as surface properties (Fritz [1], Borinshansky and Fokin [2], Ruckenstein [3], Cole and Shulman [4], Cole [5], Cole and Rohsenow [6], Kutateladze and Gogonin [7], Jensen and Memmel [8], Kim and Kim [9], Fazel and Shafaee [10], Hamzekhani et al. [11]).

The correlations of the second type usually incorporate the bubble growth rate (Golorin et al. [12], Zeng et al. [13], Yang et al. [14]). In Golorin et al. [12], β_d is a term related to the bubble growth rate, and $\beta_d = 6.0$ for water, alcohol and benzene. Analytical models about bubble growth (Zuber [15], Cooper and Lloyd [16], Mikic et al. [17]) have been developed. Recently, experimental and numerical investigations (Mukherjee and Dhir [18], Siedel [19]) were also conducted on the bubble growth, as well as the interaction and coalescence of adjacent bubbles.

Besides all these correlations, other efforts have been done to explore bubble departure diameters. Gravity effects on bubble departure diameter were studied. Kim [20] made good reviews

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Nomenclature

a	the length of the horizontal axis of a departure bubble (m)
A	amplitude, a parameter in Gaussamp function
AAD	the average absolute deviation (%)
AD	the average deviation (%)
Ar	Archimedes number, $Ar = [g\rho_l(\rho_l - \rho_v)/\mu_l^2][\sigma/g(\rho_l - \rho_v)]^{3/2}$
$a(t)$	bubble growth rate (m s^{-1})
b	the length of the vertical axis of a departure bubble (m)
Bo	Bond number, $Bo = gD_d^2(\rho_l - \rho_v)/\sigma$
c	the length of the vertical axis of the upper part of a departure bubble (m)
C	a parameter given by Borinshansky and Fokin [2] or Cole and Rohsenow [6]
Ca	capillary number
C_d	a bubble drag coefficient in Cole [43]
C_f	drag coefficient
c_p	specific heat capacity (J kg^{-1} K^{-1})
d	the length of the vertical axis of the lower part of a departure bubble (m)
d_1, d_2	a parameter in Golorin et al. [12]
d_w	contact diameter (m)
d^*	the gap between roughness elements with the same order of magnitude as the roughness height (mm)
D_d	bubble departure diameter (m)
$D_{d,m}$	mean bubble departure diameter (m)
D_F	diameter with Fritz [1]
f	bubble departure frequency (Hz)
g	gravitational acceleration (m s^{-2})
h	heat transfer coefficient (kW m^{-2} K^{-1})
h_{lv}	latent heat (J kg^{-1})
Ja	Jacob number, $Ja = \rho_l c_p \triangle T/(\rho_v h_{lv})$
Ja^c	modified Jacob number in Cole and Rohsenow [6], $Ja = \rho_l c_{pl} T_c/(\rho_v h_{lv})$
K	an empirical value in bubble growth rate in Zeng et al. [13]
K_1	a parameter defined by Jensen and Memmel [8], $K_l = (Ja/Pr_l)^2(Ar)^{-1}$
L	the calibrated length of the ruler (m)
m	an empirical exponent
n	an empirical value in bubble growth rate
N	the number of bubbles
P	pressure (MPa)
Pr	Prandtl number, Pr = ??c_p/??
q	heat flux (kW m^{-2})
R	Radius in Eq. (19)
s_1, s_2	fitting parameters in Eqs. (29) and (30)
t	time (s)
T	temperature (K)
T_c	critical temperature (K)
t_G	growth time (s)
t_W	waiting time (s)
$\triangle T$	surface superheat (K)
u	velocity (m s^{-1})
v_1, v_2	fitting parameters in Eq. (41)
V	volume in Eq. (2)
w	width, a parameter in Gaussamp function
x	a parameter in Eq. (39)
X_1, X_2, X_3	pixels of L, a and b respectively (pixel)
y	the relative frequency of bubble departure diameter
y_0	offset, a parameter in Gaussamp function

Greek letters

α	thermal diffusivity (m^2 s^{-1}), $\alpha = \lambda/(\rho c_p)$
β	the mean linear thermal expansion coefficient for stainless steel relative to 299.15 K
β_d	a coefficient related to the growth of vapor bubbles
β^*	the proportionality factor
δ	thermal layer thickness
ε	a factor that represents the effect of superheat in Yang et al. [14]
??	percentage of data predicted within ±30% deviation (%)
θ	contact angle, deg
??	thermal conductivity (W m^{-1} K^{-1})
μ	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})
ψ	a modified factor in Yang et al. [14]

Subscripts

l	liquid phase
s	saturation state
v	vapor phase
w	wall

on reduced gravity boiling heat transfer, which showed that gravity level was one of the important parameters in analyzing bubble sizes. Numerical simulation, as the advances in computing power and modeling techniques, has also been a successful approach for modeling bubble dynamics. Dhir [21] presented a review of numerical simulation of pool boiling. The predictions of bubble departure diameter were included as well as other influencing parameters.

For bubble departure frequency, most of the correlations were before 1970. It usually correlates with bubble departure diameter and can be written in this form:

$$fD_d^m = f(\rho_l, \rho_v, g, \sigma, \alpha_l, Ja) \tag{1}$$

where exponent m is an empirical value. $fD_d{}^m$ is fitted as a function of liquid and vapor density, gravity level, thermal diffusivity and so on. From Table 2, three products, $fD_d^{1/2}$, fD_d, fD_d^2, are respectively considered to find their relationship with other influencing parameters. Recently, Kim et al. [22] used wire heaters immersed in FC-72 coolant and water for investigations of pool boiling. Regardless of heat flux, the relationship between f and D_d was found to be written as $fD_d^{4.85} = 7.2 \times 10^{-8}$. From the pentane pool boiling on artificial nucleation sites, Siedel et al. [19] found that the bubble frequency was proportional to the wall superheat, and fD_d was also proportional to the wall superheat. The complexity of predicting the relationship between the bubble departure diameter and bubble departure frequency is not only due to the effects of thermodynamic properties but also the influence of the heated surface roughness. As the experiments shown in McHale and Garimella [23], the surface roughness was one of the important affecting parameters.

As mentioned above, many efforts have been devoted to investigating bubble departure mechanisms. However, owing to the complexity of boiling phenomena, correlations to predict bubble departure diameter or bubble departure frequency remain a hotspot. Moreover, methane as the working fluid in pool boiling experiments, especially its departure behavior, can hardly be found in the published literature. Methane, as the predominant component of the liquefied natural gas (LNG), is important for the sustainable growth of economy and society all over the world. Due to its much larger density than the gaseous state, it can be stored