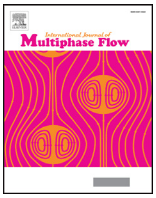
International Journal of Multiphase Flow 000 (2017) 1–12

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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



Bubble departure characteristics in a horizontal tube bundle under cross flow conditions

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ARTICLE INFO

Article history:
Received 23 January 2017
Revised 18 December 2017
Accepted 18 December 2017
Available online xxx

Keywords:
Boiling
Tube bundle
Bubble
Heat transfer
Departure diameter
Departure frequency

ABSTRACT

The visualization experiments for measuring departure diameter and frequency of vapor bubbles in the saturated nucleate boiling of distilled water have been carried out at atmospheric pressure. The experiments were carried out for an isolated single cylindrical tube and that for a tube bundle under pool and cross flow boiling conditions. The test setup was a stainless steel cuboidal tank of dimensions 400 mm × 200 mm × 180 mm provided with a 5 × 3 staggered tube bundle with an equilateral triangular pitch of 1.95. The departure diameter and frequency were measured using a high-speed camera to understand the parametric behavior of the bubble departure characteristics in a tube bundle under pool and cross flow condition. The range of operating conditions was: (1) heat flux $q'' = 8 - 28\ kW/m^2$, (2) wall superheat $\Delta T_{sat} = 7 - 22\ K$, (3) inlet mass flux $G = 120 - 303.5\ \mathrm{kg/m^2\ s}$. The departure diameter and frequency were found to increase with an increase in the heat flux, but decrease with an increase in the mass flow rate. The local departure diameter and frequency were observed to increase as the neighboring tubes in the bundle were successively heated. Empirical correlations have been developed for departure diameter and frequency for saturated nucleate boiling under cross flow conditions incorporating the effect of the tube bundle. The correlations were found to predict experimental data within acceptable limit.

1. Introduction

Nucleate boiling heat transfer is a highly desirable phenomenon due to its capability of transferring high amounts of heat at relatively low wall temperatures. It has been widely established that heat transfer can be enhanced in a bundle compared to a single tube heater under certain conditions. Such cross flow boiling in horizontal tube bundles finds applications in a number of systems like, flooded evaporators, shell and tube heat exchangers, core of a pressurized heavy water reactor, etc. The two-phase heat transfer from each of the heated tube in the bundle consists of contributions from single phase convective heat transfer, latent heat transfer due to bubble formations and departure, and bubbles originated on lower tubes sliding along the sides of the upper tubes.

A large number of studies have been carried out to study the effect of tube spacing or pitch to diameter ratio (P/D) on the local and overall heat transfer in a tube bundle. Some of the studies attribute the enhanced heat transfer to the bubbles sliding along the sides of the upper tubes, having been originated on the lower heated rods. Also, the heating of the lower tubes increases the liquid velocity adding to the convective heat transfer of the upper tubes. However, there has been an overlook of the bubble behavior on the individual tubes under the bundle effect. The bubble growth and departure on each tube in the bundle would be affected by the other heated neighboring tubes, which would significantly contribute to the local heat transfer. In this study, experiments were carried out to understand the vapor bubble departure characteristics under the effect of the presence of other heated tubes in the bundle in addition to the effects of the operating conditions like, applied heat flux, wall superheat and liquid flow velocity.

2. Literature review

The bubble departure characteristics have been studied for over six decades owing to their importance in the prediction of the two-phase heat transfer. The bubble departure diameter and frequency for pool boiling conditions have been studied in detail, both experimentally and analytically. Table 1 gives a summary

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https://doi.org/10.1016/j.ijmultiphaseflow.2017.12.013
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Please cite this article as: P. Goel et al., Bubble departure characteristics in a horizontal tube bundle under cross flow conditions, International Journal of Multiphase Flow (2017), https://doi.org/10.1016/j.ijmultiphaseflow.2017.12.013

Nomenclature

B	horizontal diameter of the spheroidal bubble (mm)
Bo	bond number ($\frac{gD_d^2(\rho_l-\rho_v)}{\sigma}$)
Bg	boiling number ($\frac{q''}{Gh_{fg}}$)
C	vertical diameter of the spheroidal bubble (mm)
C_1, C_2	model constant
C_p	specific heat capacity at constant pressure (kJ/kg.K)
CHF	critical Heat Flux (kW/m^2)
D_d	equivalent departure diameter (mm)
D	heater tube diameter (mm)
E	enhancement factor
f	bubble departure frequency (Hz)
g	acceleration due to gravity (m/s^2)
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^{2}K)
h_L	single phase forced convective heat transfer coefficient (W/m^{2}K)
h_{pb}	pool boiling heat transfer coefficient (W/m^{2}K)
h_{fg}	latent heat of vaporization (kJ/kg)
I	current (A)
Ja	Jakob number ($\frac{\rho_l C_p \Delta T}{\rho_v h_{fg}}$)
k	thermal conductivity (W/m.K)
n	number of heated tubes in the bundle
Nu_B	Nusselt number for boiling, ($\frac{h}{k}\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}$)
p	pressure (bar)
P/D	pitch to diameter ratio
Pe	Péclet number (Re. Pr)
Pr	Prandtl number ($\frac{C_p\mu}{k}$)
q"	heat flux (kW/m^2)
R_a	average surface roughness value (μm)
Re	Reynolds number ($\frac{\rho_l v D}{\mu}$)
Re_B	Reynolds number for boiling, ($\frac{q''}{\mu h_{fg}}\sqrt{\frac{\sigma}{\rho_l-\rho_v}}$)
t	time (ms)
t_g	bubble growth time (ms)
t_w	bubble waiting period (ms)
T	temperature (K)
ΔT_{sat}	degree of wall superheat (K)
v	liquid bulk velocity (m/s)
V	volume (m^3)
V_o	voltage (V)

Greek symbols

α	thermal diffusivity (m^2/s)
θ	contact angle (radians)
σ	surface tension (N/m)
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa.s)

Subscripts

l	liquid
v	vapor
sp	sphere
b	bubble

of the pool boiling experiments conducted at atmospheric pressure to measure bubble departure diameter (D_d) and frequency (f). Fritz (1935) proposed the first empirical correlation for bubble departure diameter by balancing the surface tension and buoyancy forces. Ruckenstein (1961) measured bubble departure diameter as a function of wall superheat and proposed a correlation for the same, in terms of Jakob number (Ja). Cole (1967) reviewed the previous models of bubble departure diameter and modified Fritz correlation by taking the effect of pressure and wall superheat into account in terms of Jakob number (Ja). Cole and Rohsenow (1969) proposed correlation for calculating bubble departure diameter at low pressures ($0.067-1$ bar) for various fluids by introducing two distinct constants- one for water and other for rest of the fluids. Kocamustafaogullari and Ishii (1983) found that the Fritz correlation yielded good agreement with experimental results only near atmospheric pressure. Hence, to account for the pressure dependence, they modified Fritz correlation by including a density ratio term. As regards to the departure frequency, the only correlation available for the prediction is the one given by Cole (1960), which was derived for near CHF conditions and is therefore, not precise for low heat flux system. These correlations are reproduced in Table 2 for reference.

Table 3 provides a summary of the vertical flow boiling experiments. Most of the studies carried out to measure bubble departure characteristics in vertical flow boiling conditions observed that the diameters tend to increase with heat flux and decrease with increase in mass flux, except Prodanovic et al. (2002) and Situ et al. (2004, 2005), who observed that the bubble diameters increase with heat flux initially but become constant at higher values of heat flux. Very few comprehensive (experimental and modeling) studies have been performed for bubble departure frequency under flow boiling condition. Although a number of such studies exist for pool boiling but the bubble departure mechanism is significantly different from flow boiling conditions. Some studies that measured the waiting period and growth period and hence, bubble frequencies, suggest that the waiting period decreases with an increase in heat flux or wall superheat while the growth time is not much affected by them, implying that the bubble departure frequency increases with an increase in the heat flux and wall superheat. The behavior of departure frequency with mass flux is also not clearly known. Also, these studies (though limited) have been carried out for the liquid motion parallel to the heater surface. However, scanty information is available in the published literature on the behavior of vapor bubbles in the scenario of the cross flow across the heater.

Leong and Cornwell (1979) working with a horizontal tube bundle (reboiler with $P/D = 1.34$) in R113 at atmospheric pressure observed a significant increase in the two-phase heat transfer in the upper tubes of the bundle compared to that of the lowest tubes. Cornwell and Schuller (1982) carried out photographic studies on the same setup and observed a large number of bubbles in turbulent flow between the upper tubes of the bundle, which originate from the heater tubes and also slide along them. They attributed the enhanced heat transfer in the tube bundles to this growth and sliding of the vapor bubbles. Gupta et al. (1995) studied the heat transfer in a horizontal tube bundle ($P/D = 1.5-6$) with tubes arranged in a vertical column. They concluded that the vapor bubbles rising from lower tubes enhance the turbulence which leads to increased heat transfer on the upper tubes compared to a single tube geometry. They also found that the heat transfer of a given tube increased with a decrease in P/D ratio. Kumar et al. (2002) measured the two-phase heat transfer of the individual tubes in a vertical stack of two copper tubes. They reported that when both the tubes were simultaneously heated, the heat transfer of the lower tube was same as when it was heated alone. However, the heat transfer of the upper tube was enhanced due to the interaction of vapor bubbles produced on the lower tube. They suggested that since the upper tube in the tube bank provided a higher heat transfer at a given heat flux, it can be considered to be working as a single tube at a higher effective heat flux ($q''_{upper} +$ a fraction of q''_{lower}). Gupta (2005) observed heat transfer of saturated water under atmospheric conditions in an 5×3 inline horizontal tube bundle ($P/D = 1.5$). He observed that the heat

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