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A critical review on bubble dynamics parameters influencing boiling heat transfer

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A R T I C L E I N F O

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A B S T R A C T

The rate of heat transfer during boiling is governed by various bubble dynamics parameters such as bubble departure diameter, active nucleation site density, bubble waiting period, bubble growth period, bubble growth rate and bubble departure frequency. The study of bubble dynamics during boiling of liquids over a heated surface is a complex process due to non-linear growth of bubbles. Many studies on bubble dynamics is carried out by both experimentally and numerically. These studies are carried to propose various empirical and semi-empirical correlations for determination of bubble dynamics parameters. In the present paper, a comprehensive review is carried out to compile various correlations proposed for determination of bubble dynamics parameters. The correlation for determination of boiling heat flux or boiling heat transfer coefficient based on these bubble dynamics parameters are reported. This is done to identify important bubble dynamics parameters affecting boiling heat transfer process. Further, factors affecting bubble dynamics parameters such as effect of thermo-physical properties, heat flux, liquid sub-cooling, wall superheat, contact angle, gravity, cavity spacing and pressure are also given to get an insight into the correlation proposed for determinations of bubble dynamics parameters. The present review article proposes the importance of development of generalized boiling heat transfer correlation using bubble dynamics parameters.

1. Introduction

Boiling is an incredible and challenging area for carrying out research activities to fulfill the requirements of various industrial/research sectors such as thermal and nuclear power plants, refrigeration and air conditioning units, rocket motors, electronics cooling, food processing and other aide industries. In boiling heat removes from the heated surface by means of vapor bubbles generated due to change of phase. Since vapor bubbles are accountable for degree of dissipation of heat by boiling heat transfer, it is significant to understand the mechanism behind the formation, growth and detachment from the boiling surface. The detachment of the vapor bubble from the surface is influenced by the various forces acting on growing bubble. Out of various forces acting on the vapor bubble during its growth, the major force responsible for attachment of vapor bubble to the heated surface is surface tension whereas the buoyancy force is accountable for detachment of the vapor bubble.

During initial growth stage of bubble the surface tension force dominants the buoyancy force. However, with increase in size of the vapor bubble, buoyancy force gradually supersede the surface tension force. When the magnitude of buoyancy force becomes much higher than the surface tension force, the vapor bubble detach from the heated surface. So, the formation, growth and detachment of the vapor bubble and the rate of heat transfer thereof requires the knowledge of bubble dynamics parameters. These bubble dynamics parameters are nucleation site density, bubble departure diameter, bubble waiting period, bubble growth period and bubble departure frequency. The determination of boiling heat transfer coefficient can be done by using either empirical or semi-empirical correlations or correlations developed using bubble dynamics parameters.

Many empirical correlations for determination of boiling heat transfer coefficient are available in the literature [1–4]. However, almost all these correlations predict own experimental results reasonably but fails to predict the experimental data of other investigators [5–10]. On the other hand, the correlations developed using bubble dynamics parameters are based on fundamentals of boiling heat transfer. It is, therefore, expected that such correlations can predict experimental data of different investigators with minimum errors. This is important to note that the accuracy of such generalized boiling heat transfer correlations are entirely dependent on the correlations developed to predict the bubble dynamics parameters. This is because the correlations developed for prediction of bubble dynamics parameters

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Nomenclature

Ar	Archimedes number $[(g/\mu_l^2)(\sigma/\rho_l g)^{3/2}]$
A	area of heated surface (m^2)
G	Average mass velocity of bubble ($\frac{\pi}{6}D_d^3\rho_v f n_s$)
Bo	Bond number ($\Delta\rho g D_d^2/\sigma$)
Bo_m	Modified Boiling number(q/Gh_{lv})
Ca	Capillary number ($\mu_v U/\sigma\cos\theta$)
C_D	drag coefficient
C_e	empirical constant =20/3
C_s	surface fluid combination factor
C_p	specific heat at constant pressure (J/kg K)
D_d	bubble departure diameter (m)
D	bubble diameter (m)
D_c	cavity diameter (μm)
$D_{d,dry}$	diameter of dry area under bubble (m)
D_1	diameter of tube (m)
D_s	diameter of heating surface
D_f	fractal dimension
dD/dt	bubble growth rate
f	bubble departure frequency (1/s)
f (c)	bubble volume factor
g	gravitational acceleration (m/s^2)
g_c	gravitational correction factor
h	heat transfer coefficient (W/m^2 K)
h_{lv}	latent heat of vaporization (J/kg)
Ja	Jakob number ($\rho_l C_{pl}(T_w-T_{sat})/\rho_v h_{lv}$)
J	latent heat removal by per bubble (J/kg)
k	thermal conductivity (W/m K)
m	empirical constant
Nu	Nusselt number (hD/k)
N	number of nucleation sites
n_s	active nucleation site density (sites/m^2)
$\overline{n_a}$	average cavity density (sites/m^2)
n_s^+	non-dimensional active nucleation site density
P	pressure (MPa)
Pr	Prandtl number ($\mu_l C_{pl}/k_l$)
q	heat flux (W/m^2)
R	gas constant (J/kg K)
R_a	surface roughness (μm)
R_c	cavity radius (μm)
R_c^+	non-dimensional critical cavity radius
r	bubble radius (m)
r_b	radius of the liquid microlayer under bubble (m)
r_t	instantaneous bubble radius (m)
r^+	non-dimensional bubble radius
s	standard deviation
T	temperature (K)
t	time (s)
t_l	bubble lift-off time (s)
t_w	bubble waiting period (s)
t_g	bubble growth period (s)
t^+	non-dimensional time
V_b	bubble velocity (m/s)
V	volume (m^3)
V_d	bubble departure volume
V^+	non-dimensional volume=(V/V_d)
ρ^+	non-dimensional density difference

Greek symbols

θ	contact angle (°)
ρ	density (kg/m^3)
Δ	difference
Φ	dimensionless surface roughness parameter
μ	dynamic viscosity (kg/m s)
β	half cone angle (°)
ν	kinematic viscosity (m^2/s)
$\bar{\beta}$	mean half cone angle (°)
∅	parameter in Eq. (13)
λ	statistical parameter
λ_T	Taylor most dangerous wave length
γ	surface-liquid interaction parameter
σ	surface tension (N/m)
δ	thermal boundary layer thickness (m)
α	thermal diffusivity ($k_l/\rho_l C_{pl}$) (m^2/s)
ε	volumetric expansion coefficient (1/K)

Superscripts

+	non-dimensional

Subscripts

c	cavity
l	liquid phase
max	maximum
me	microlayer evaporation
min	minimum
nc	natural convection
b	boiling
r	reduced property
sat	saturation condition
tc	transient conduction
s	heating surface
v	vapor phase
w	wall
∞	bulk

are again influenced by various parameters. Owing to the above facts, initially a review is carried out on existing boiling heat transfer correlations to predict boiling heat transfer coefficient and boiling heat flux based on bubble dynamics parameters. These correlations are used to predict experimental data of other investigators to find its appropriateness as a generalized correlation. The bubble dynamics parameters addressed in these correlations are then identified. Based on these information, a comprehensive review is carried out on these bubble dynamics parameters and factors affecting them. This include review of existing correlations, their comparison in predicting experimental data of different investigators etc. Thus, this review may help the researchers to develop generalized boiling heat transfer correlations based on bubble dynamics parameters which may be applicable for wide range of operating parameters.

Fig. 1 shows inter-functional dependency of bubble dynamics parameters in the determination of boiling heat transfer coefficient. The flow chart is developed by considering the two independent factors i.e. wall superheat and force balance on the vapor bubble during growth and detachment from the heated surface. The other bubble dynamics parameters are correlated with one another with a view to predict the boiling heat transfer coefficient. This flow chart gives the basic and root level idea about the interconnections of bubble dynamics parameters with boiling heat flux or boiling heat transfer coefficient.

2. Boiling heat transfer coefficient and boiling heat flux

The important objective in boiling process is to determine the boiling heat transfer coefficient or boiling heat flux. The different