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A scale analysis model for film boiling heat transfer on a vertical flat plate with wide applicability

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ABSTRACT

A model has been developed in present work, for a vertical flat plate under film boiling condition, based on scale analysis. The saturated and subcooled film boiling have been analyzed from heat and mass transfer consideration and appropriate vaporization criteria. The model takes care of natural convection and forced convection mode of heat transfer for subcooled case, while the saturated film boiling is treated with an assisting convection mode. The interfacial wave length is incorporated into the length scale and the effect of radiation heat transfer is accounted in the model. Expressions for Nusselt number have been developed for different situations. The present model recovers the Bromley scale for natural convection under saturated condition. The heat transfer characteristic is shown for relevant non-dimensional numbers pertaining to film boiling for various cases. A wide set of existing experimental data with ranges of wall superheat 260–1200 °C, liquid subcooling 0–50 °C and flow velocity 0–2.65 m/s have been systematically utilized to arrive at the model closure.

1. Introduction

The analysis of film boiling has been attracting several researchers since long due to its varied applications in nuclear reactors [1], cryogenic engineering [2] and manufacturing science [3]. Recently film boiling process is utilized successfully in chemical synthesis [4,5]. A detailed theoretical analysis of such problems is quite challenging due to the concurrent presence of liquid and vapor phases with widely varying thermo-physical properties and the mass and energy transfer associated with phase change.

A significant volume of research was devoted to understand the underlying mechanism of heat and mass transport involving phase change during film boiling in basic geometries. Starting from the pioneering work of Bromley [6] on film boiling, Dhir and Purohit [1], Zumbrunnen et al. [3], Frederking and Hopenfeld [7], Shiotsu and Hama [8], Kolev [9], Jouhara and Axcell [10] and Meduri et al. [11] carried out extensive experimental and numerical analyses. Some experiments [1,8,10,11] involved appropriate visualization studies and measurement of heat transfer during quenching of a surface from a high temperature. The wall superheat and liquid subcooling were considered as the main parameters, along with other relevant thermo-physical properties of liquid and vapor phases. The theoretical analyses were based on either integral method [1,8,10] or similarity transformations [3,7] with two-phase boundary layer approximations over plate, cylinder or spherical geometries. The analyses considered the role of nondimensional numbers, representative of both superheated vapor and subcooled liquid layers. In recent past, the direct numerical simulations with appropriate computational techniques have been employed for understanding the complex flow pattern and bubble release mechanism under film boiling condition [12–14].

The roles of the interfacial instabilities on the heat transfer and hydrodynamics of film boiling were emphasized by Nishito and Ohtake [15], Vijaykumar and Dhir [16] and Bui and Dhir [17]. The hydrodynamic instabilities and wavelength patterns with the intermittent bubble release under saturated and subcooled conditions were analyzed. Kolev [9], Okkoken [18], Das et al. [19], Bazdidi-Tehrani and Zaman [20] and Arias [21] used the findings of these experiments to select the characteristics length scale in their analyses. For instance, Nishito and Ohtake [15] and Okkoken [18] used the Kelvin–Helmholtz instability length scale, Meduri et al. [11] employed capillary wavelength scale and Das et al. [19] used the Rayleigh–Taylor length scale to correlate the heat transfer data for vertical flat plate and tubes. Each of these predictions revealed good agreement with pertinent experimental results over certain restricted parameter range. The improvements have been significant with respect to the gross underprediction of the plate length based analyses.

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Nomenclature

g	acceleration due to gravity
Gr_l	liquid phase Grashof number = $g\beta_l(T_{sat} - T_\infty)L_c^3/\nu_l^2$
Nu_R	convective heat transfer coefficient
h_{fg}	latent heat of evaporation
Ja_{sub}	liquid-phase subcooling Jakob number = $c_{pl}(T_{sat} - T_\infty)/h_{fg}$
Ja_{sup}	vapor-phase superheat Jakob number = $c_{pv}(T_w - T_{sat})/h_{fg}$
j	mass flux
k	thermal conductivity
L_c	instability length scale = $\left[\sigma_t/\{g(\rho_l - \rho_v)\}\right]^{1/2}$
Nu	Nusselt number = $h_{conv}L_c/k_v$
p	pressure
Pr_l	liquid-phase Prandtl number
Pr_v	vapor-phase Prandtl number
Ra_l	liquid-phase Rayleigh number = $g\beta_l(T_{sat} - T_\infty)L_c^3/(\nu_l\alpha_l)$
Ra_v	vapor-phase Rayleigh number = $g(\rho_l - \rho_v)L_c^3/(\rho_v\nu_v\alpha_v)$
Re_l	liquid-phase Reynolds number = $(u_\infty L_c)/\nu_l$
R_q	heat transfer ratio
s_{nu}	scale factor
T	temperature
u, v	velocity components
x, y	coordinates

Greek symbols

α	thermal diffusivity
β	coefficient of volumetric thermal expansion
δ	vapor film thickness
δ_l	liquid momentum boundary layer thickness
δ_t	liquid thermal boundary layer thickness
ε	emissivity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	Stefan–Boltzmann constant
σ_t	surface tension

Subscripts

eq	equivalent
$\exp t$	experimental value
$\exp t, c$	convective part of experimental value
hs	high superheat
$lsfc$	low superheat forced convection
$lsnc$	low superheat natural convection
i	interface
l	liquid
r	radiation
sat	saturation
tot	total
v	vapor
w	wall of the plate
∞	free stream

In contrast to the prevalent trend of experimental and numerical analyses, Berthoud and D'Aillon [22] carried out a scale analysis for the film boiling problem on horizontal cylinders. Their analysis considered the high subcooling and high superheat cases separately. The scale analysis was performed along with stagnation flow approximation and validated against forced convection experiments on a micron size wire. Clearly this scale analysis cannot be applied for a plate, where natural convection can also become important on certain situations.

Under the circumstances, a generalized scale analysis has been taken up for prediction of heat transfer during film boiling for a vertical plate under different conditions. The effects of the natural convection and the forced convection have been treated separately, based on scaling argument. The extreme conditions include high-superheat-low-subcooling situation for wall and water respectively and low-superheat-high-subcooling situation. Each case is treated with a rational criterion, based on interfacial mass and energy balance in vapor and liquid layer and a parametric vaporization representation. The effect of length scale of the problem is resolved following an approach of Meduri et al. [11], taking the interfacial wave into consideration. Present analysis recovers the basic Bromley scale for natural convection film boiling under saturated condition.

The present model is validated with various experimental data of heat transfer from different investigators for vertical flat plate for a wide range of parametric conditions. Typically a wall superheat ranging from 260–1100 °C, subcooling varying between 0 to 60 °C and liquid flow velocity in the range from 0 to 2.65 m/s have been considered for obtaining the model closure. The objective of the present work is to address the film boiling heat transfer for vertical plate geometry in a comprehensive way, solely from a perspective of simplified scaling law.

2. Mathematical model

Fig. 1 shows the possible velocity and temperature profiles in case of film boiling on a hot vertical wall at a temperature T_w of a liquid with far stream temperature T_∞. Two principle mechanisms for the flow in the two-phase domain are the natural convection of the lower-density vapor phase near the wall and the forced convection of the bulk liquid phase with a far stream velocity of say, u_∞. Of course, the effect of the forced convection of a subcooled liquid can be seen as a means of suppressing the vapor raising. The vapor raising mechanism is weaker, also for a wall with relatively lower superheat. Hence, the growth of the vapor layer thickness δ along the vertically upward direction x is understandably shown as the slowest in Fig. 1(c) for the combination of low wall superheat and domination of forced convection in the liquid. Fig. 1(b) shows this growth rate to be higher for the combination of low wall superheat and domination of natural convection in the liquid phase. The far-stream liquid velocity turns out as the highest in Fig. 1(c). On the other hand, Fig. 1(b) shows the velocity peak occurring inside the vapor phase. While the flow in the first case is dominated by the far-stream flow, in the latter case the relatively stronger evaporation acts as the dominating flow mechanism. Of course, the velocity profile for the case of high wall superheat shown in Fig. 1(a) resembles Fig. 1(b), irrespective of the domination of the forced or natural convection in the liquid phase. The growth of the vapor layer in the last case should clearly be the highest.

Different considerations used in accomplishing a scale analysis of the film boiling for all these cases are listed next.

1. Based on the analysis by Meduri et al. [11], the length scale along the x direction is determined following a unit wavelength approximation of