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On the development of a thin evaporating liquid film at a receding liquid/vapour-interface

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ABSTRACT

In nucleate boiling two specific models are used to describe wall heat transfer to single bubbles: (i) The contact line model, in which evaporation close to the three-phase contact line is the dominating effect, and (ii) the microlayer model, in which evaporation of a thin liquid film below the bubble is the dominating effect. These models are discussed controversially in literature. In this work high speed IR thermography is used to investigate influence factors onto the development of such a thin, evaporating liquid film at a single receding meniscus. FC-72 is used as working fluid. From the time-dependent temperature field the evolution of the local heat flux is derived numerically. Both situations could be observed, contact line, as well as microlayer evaporation, depending on the experiment parameters. Through comparative analysis, the velocity of the interface, the wall superheat and the latent heat of evaporation are found to have a major influence. Furthermore the wetting characteristics of the heated wall have an influence onto the incipience of thin film deposition. From a stationary mass and energy balance at an infinitesimal short segment of the thin evaporating film an equation for the local gradient of the film thickness is obtained. Integration of the dimensionless form of this equation results in a description of the film thickness and the local heat transfer at such a thin evaporating film. Three dimensionless groups are found to have an influence onto the film thickness profile. A comparison of the model to experimentally determined values shows good agreement.

1. Introduction

Phase change processes involving a moving liquid/vapour-interface at a solid are of high importance in many technical applications, e.g. in pool and flow boiling heat transfer equipment. In these cases evaporation takes place near the nucleation sites at a heated wall, which makes it necessary to include conjugate solid/fluid heat transfer to describe the process with a physically accurate model. In literature, two different, specific models, that are illustrated in Fig. 1, have been suggested to describe the wall heat transfer to growing bubbles on the microscale.

(i) The microlayer model
The microlayer model was first proposed by Snyder and Edwards [1]. In this model it is assumed that the vapour bubble growth is so fast, that a thin liquid film (with a thickness ranging from few to several tens of μm) is trapped due to viscous forces in the liquid phase between the growing vapour bubble and the heater wall. According to Cooper [2] the thickness of this liquid layer decreases with the square root of time through evaporation at the microlayer/bubble-interface. This microlayer evaporation is supposed to contribute a significant amount to the overall evaporation rate associated with the bubble cycle.

(ii) The contact line model
This model assumes, that no microlayer is deposited on the heater surface by the vapour bubble growth. In this case evaporation in the vicinity of the three-phase contact line plays an important role. The contact line model takes the influence of attractive intermolecular forces between the wall molecules and the molecules at the liquid/vapour-interface into account. These forces represent an additional resistance against evaporation, that can be expressed as a shift of the phase equilibrium to higher interfacial equilibrium temperatures. As a result, an apparent dry region beneath the bubble is covered by a thin adsorbed film with a thickness in the order of a few nm. This film can not be evaporated due to the intermolecular forces (adsorbed film region). These forces decay very rapidly as the film gets thicker in a transition region (micro region) between adsorbed film and bulk liquid (macro region). The concept

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Nomenclature

Latin characters

c	specific heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
E	energy flow per unit depth ($\mathrm{W\,m^{-1}}$)
g	gravitational acceleration ($\mathrm{m\,s^{-2}}$)
h	heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
h_{lv}	latent heat of evaporation ($\mathrm{J\,kg^{-1}}$)
I	current (A)
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
l	length (m)
M	mass flow per unit depth ($\mathrm{kg\,s^{-1}\,m^{-1}}$)
p	pressure ($\mathrm{N\,m^{-2}}$)
q	heat flux ($\mathrm{W\,m^{-2}}$)
R	electrical resistance (Ω)
r	radial coordinate parallel to the heater wall with $r = 0$ at the nucleation site (m)
s	axial coordinate perpendicular to the heater wall with $s = 0$ at the nucleation site (m)
T	temperature (K)
t	time (s)
v	velocity ($\mathrm{m\,s^{-1}}$)
w	width (m)
$x,\ y,\ z$	Cartesian coordinates (m)

Greek characters

α	thermal diffusivity ($\mathrm{m^2\,s^{-1}}$)
δ	liquid film thickness (m)
μ	dynamic viscosity ($\mathrm{Pa\,s^{-1}}$)
ν	kinematic viscosity ($\mathrm{m^2\,s^{-1}}$)
ρ	density ($\mathrm{kg\,m^{-3}}$)
σ	surface tension ($\mathrm{N\,m^{-1}}$)

Subscripts

0	reference
abs	absolute
crit	critical
evap	evaporation
hl	heating layer
in	input
int	interface
l	liquid
num	numerical
R	reduced
rel	relative
sat	saturation conditions
tf	thin film/microlayer
w	wall

Dimensionless numbers

$A = \mathrm{Ja}/(\mathrm{Pr\,Re})$	model parameter
$B = \mathrm{Bo}/\mathrm{Ca}$	model parameter
$C = \mathrm{Ja}$	model parameter
$\mathrm{Bo} = \rho g l_0^2/\sigma$	Bond number
$\mathrm{Ca} = \nu \rho v_0/\sigma$	capillary number
$\mathrm{Ja} = c_{\mathrm{l}}(T_{\mathrm{w}} - T_{\mathrm{w}})/h_{\mathrm{lv}}$	Jakob number
$\mathrm{Nu} = h l_0^2/k$	Nusselt number
$\mathrm{Pr} = \nu/\alpha$	Prandtl number
$\mathrm{Re} = v_0 l_0/\nu$	Reynolds number

of including intermolecular forces in the description of three-phase contact lines was first proposed by Wayner [3]. Later Stephan and Hammer used this modelling approach to describe heat transfer at the contact line of vapour bubbles during pool boiling [4]. Since the liquid film in the micro region is very thin and thereby its heat resistance is very small, high evaporation rates are to be expected in this region and therefore its contribution to the overall heat transfer of a single bubble is expected to be of high significance.

There is experimental evidence both for the existence of a microlayer heat transfer dominated case (e.g. by Judd and Hwang [5] and Fath and Judd [6]), as well as for a contact line heat transfer dominated case (e.g. by Wagner et al. [7] and Wagner and Stephan [8]). A comprehensive review of experimental work conducted on single bubble heat transfer with special attention to these two (and several other) models is given by Kim [9]. From the experimental data available in literature no clear conclusion can be drawn so far on when wall heat transfer to a bubble occurs in the contact line dominated mode and when in microlayer dominated mode. However, Fath and Judd reported a bigger contribution of microlayer heat transfer to the total energy of a bubble under lower experiment pressures [6]. Kim reasoned that the Jakob number, which is given by

$$\mathrm{Ja} = \frac{c_{\mathrm{l}}(T_{\mathrm{w}} - T_{\mathrm{sat}})}{h_{\mathrm{lv}}}, \tag{1}$$

influences the contribution of microlayer evaporation [9]. The lower the Jakob number, the bigger is the contribution of microlayer evaporation. This is in line with the results of Fath and Judd [6], as lower experimental pressure results in higher latent heat h_{lv} and thereby a lower Jakob number. Kim supported his hypothesis through a comparison of the Jakob numbers of different experimental data sets of several research groups, which confirmed the trend that microlayer evaporation seems to be of higher importance, when the Jakob number is rather low.

The local heat flux profiles that are to be expected from the different heat transfer modes are depicted in Fig. 2. Since the radial extension of the micro region in the contact line model is very small, a sharp heat flux peak is to be expected in this area. In the microlayer model in contrast, the much larger region below the microlayer should exhibit higher heat flux than in the bulk liquid region, that gradually increases in direction of the dry region, as the liquid film gets thinner. The highly dynamical nature of single bubble heat transfer makes it extremely difficult to quantify in situ the influence of the Jakob number on the wall heat transfer mode.

The aim of this paper is therefore to identify influence parameters on the generation of such a microlayer or contact line region in an experimental setup, in which the velocity of the liquid/vapour-interface is not pre-determined through bubble dynamics, but a controlled parameter. A generic experiment was built, in which the local heat transfer at a moving single extended meniscus is investigated through high speed infrared (IR) thermography. From the measured time and space resolved temperature data and the numerically calculated heat flux distributions conclusions can be drawn on whether contact line or thin film evaporation is the dominant heat transfer mode.

2. Experiment setup and data reduction

A schematic of the experiment test section is displayed in Fig. 3. A single capillary slot with a width of 1.4 mm is generated in between a polished copper wall and a heated wall. The heated wall