Nuclear Engineering and Design xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Mechanistic studies of single bubble growth using interface-tracking methods

Susann Hänsch [a,*], Simon Walker [a], Chidambaram Narayanan [b]

[a] Department of Mechanical Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, United Kingdom
[b] Ascomp AG, Switzerland

HIGHLIGHTS

- Validation of a phase change model at the curved vapour-liquid interface.
- Analysis of different approaches for modeling the microlayer evaporation.
- Significance of conjugate heat transfer for microlayer evaporation.
- Role of evaporative thermal resistance for evaporation from the microlayer.
- Mechanistic simulation of the hydrodynamics of microlayer formation.

ARTICLE INFO

Article history:
Received 31 May 2016
Received in revised form 22 July 2016
Accepted 3 August 2016
Available online xxxx

ABSTRACT

The growth of a vapour bubble at a heated surface involves various fluid mechanics, heat transfer and phase change phenomena. In this paper we present recent work under the auspices of the NURESAFE project aimed at developing mechanistic modelling of this. Evaporation at the curved surface of the bubble requires evaluation of the unsteady heat conduction within the surrounding liquid, coupled to an appropriate phase change model at the vapour–liquid interface. Issues around the development and implementation of such a phase change model are addressed. For low-pressure bubbles, however, a large fraction of the total evaporation takes place from the "microlayer"; a thin layer of water coating the heated substrate, which is left behind as the bubble expands. This microlayer evaporation requires careful, sub-grid modelling, as heat fluxes through the thin layer are very high. In particular, we demonstrate here the need both for modelling of the conjugate heat transfer within the substrate, and the importance of the incorporation of evaporative thermal resistance at the vapour–liquid interface. Despite the important role it plays in bubble growth, the mechanisms governing the formation, and resulting dimensions, of this microlayer are very little understood. We finish with a presentation of some early results attempting to investigate mechanistically the hydrodynamics of microlayer formation.

1. Introduction

A thorough understanding of the fundamentals of the boiling process on the scale of single bubbles is crucial for the further improvement of macroscopic boiling models. There is an emerging consensus about the various physical processes involved in the growth and the departure of steam bubbles from heated surfaces. Much effort has been applied to develop understanding and modelling capabilities for these processes, which can be incorporated into micro-scale simulations that allow detailed analysis of the growth of a single bubble.

Vapour generation during nucleate boiling is now known to occur in two different regions around the bubble as illustrated in Fig. 1.

Bubble growth is partly driven by evaporation from the bubble's curved surface, caused by a superheated liquid layer around the bubble, also termed the 'relaxation' layer. The ability to predict accurately the interphase mass transfer from such curved surfaces is essential for the simulation of any phase change phenomena using interface-tracking techniques.

The other mechanism is the evaporation of a thin layer of liquid beneath the steam bubble, which is termed the 'microlayer'. The microlayer can develop during the early stages of bubble growth, when the expanding bubble leaves behind a liquid layer a few microns thick between the heated wall and the underside of the bubble. Being all that separates the superheated wall from the

* Corresponding author.
E-mail addresses: s.haensch13@imperial.ac.uk (S. Hänsch), narayanan@ascomp.ch (C. Narayanan).

http://dx.doi.org/10.1016/j.nucengdes.2016.08.003
0029-5493/

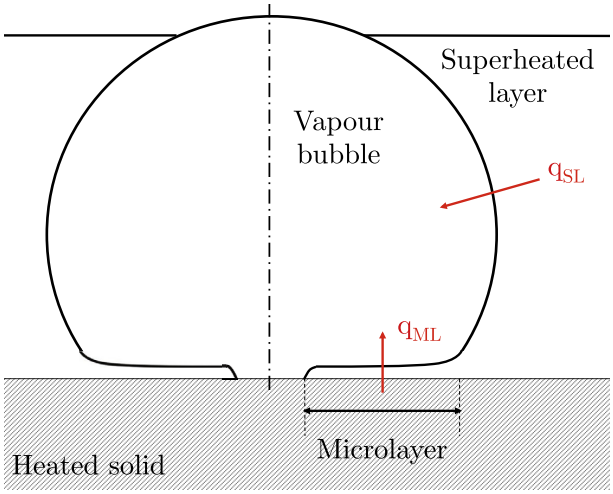

Fig. 1. Vapour generation mechanisms during bubble growth.

vapour, the microlayer evaporates rapidly and can contribute significantly to the bubble's growth.

The contribution of each of these evaporation mechanisms to the overall bubble growth is still debated in the literature and indeed their relative importance depends on the particular conditions that obtain. Table 1 lists typical physical parameters for steam bubbles measured in experiments at atmospheric pressure (Jung and Kim, 2015) and at a higher pressure (Sakashita, 2011). For high-pressure bubbles the bubble growth rate is generally much smaller than at atmospheric pressure with small departure diameters of ~100 μm for similar departure times. Microlayers are not observed at all and their contribution to vapour generation is believed to be minimal under high-pressure conditions (Sakashita, 2011). On the contrary, atmospheric pressure bubbles tend to be much larger by the time they depart, and during this growth do tend to leave microlayers beneath them, and the evaporation of these microlayers plays an important role in the growth and eventual departure of such bubbles.

This paper reports recent work under the NURESAFE project investigating the performance of various aspects of the modelling of mass transfer and bubble growth in interface-tracking CFD analysis of microscopic boiling.

Section 2 will focus on the evaporation from the curved surface. The approach used in this work in essence, by construction, takes the interface temperature to equal the saturation temperature at the relevant pressure, and models the rate of vapour generation as being determined by the heat flux to the interface from the superheated surrounding liquid. This heat flux is itself a consequence of the transient radial temperature gradient, as the temperature reduction propagates back into the bulk of the liquid.

In Section 3 we address the related but different issues associated with heat transfer through and mass transfer from the microlayer. In the literature there are two broad approaches, the "triple line" description of evaporation, and 'whole microlayer' models. We investigate these, and discuss recent improvements to the current state-of-the-art in microlayer mass transfer modelling. In particular, we will address the significance of conjugate heat transfer in the heated wall, and the role that evaporative resistance is believed to play in the microlayer region.

Despite their probably dominant role in much bubble growth, the mechanism for the formation of microlayers is little understood, and the modelling tends to be based upon empirical incorporation of very sparse experimental data. In Section 4 we present simulations of the hydrodynamics of microlayer formation during the very early stage of bubble growth. These simulations aim to add to the understanding of the underlying processes that lead to the formation of microlayers and the physical quantities governing their characteristics.

Conclusions and suggestions for possible future directions of research are presented in Section 5.

Table 1
Typical physical parameters for bubbles at atmospheric and high-pressure conditions.

Physical parameter	Atmospheric bubble	High pressure bubble
Pressure [MPa]	0.1	4.47
Departure diameters [mm]	~4	~0.1
Departure period [ms]	~20	10
Average growth rate [mm/s]	100	5
Observed microlayers	Yes	No

2. Macroscopic phase change model

2.1. Introduction

The physical phenomena of interfacial mass transfer, as it occurs in boiling or condensing flows, and the associated temperature distribution near the gas–liquid interface are areas of active research. In recent years, a number of different models have emerged that examine the nature of the liquid and vapour states, and the transition between them, from different points of view. In a macroscopic treatment of boiling, in which phases coexist, the boundary between them is usually idealized as a surface at which discontinuity in properties occurs. At a much smaller scale there is a region between the bulk phases in which the molecules exhibit a transition between vapour and the liquid properties. These different points of view led to the development of a number of different phase change models over the last decades.

With increasing computer power and use of CFD some of these phase change models have been successfully incorporated into interface tracking simulations, where phase change processes are described with the tools of continuum mechanics.

In this section the physical basis of a phase change model is described, followed by a discussion of its inclusion into the level-set code TransAT.

2.2. The physical basis

In microscopic boiling modelling, it is normal to begin with a tiny, but arbitrarily sized vapour 'seed'. In the 'relaxation' approach adopted here, this vapour is taken to be at the saturation temperature. At the beginning of the analysis the surrounding liquid is taken to be at a uniform temperature, at a few degrees of superheat.

The liquid–vapour interface is taken to be at the saturation temperature, and this causes a transient diffusive reduction in temperature to propagate into the liquid (not unlike the normal error function solution for a suddenly-imposed step change in surface temperature of a medium). This is indicated qualitatively in Fig. 2.

This is of course associated with a (high) heat flux from the superheated liquid towards the saturation-temperature interface, and this heat flux is taken to cause the generation of saturated vapour, with the rate given by the relationship

$$\dot{m}''_{vapour} = \frac{1}{h_{fg}} k_l \frac{\partial T}{\partial n} \tag{1}$$

Note that this approach (implicitly) treats the actual process of evaporation at the surface as 'perfect', in that it offers no impediment to the vapour generation. We will return to this point shortly.

Please cite this article in press as: Hänsch, S., et al. Mechanistic studies of single bubble growth using interface-tracking methods. Nucl. Eng. Des. (2016), http://dx.doi.org/10.1016/j.nucengdes.2016.08.003