TSINGHUA SCIENCE AND TECHNOLOGY
ISSN 1007-0214 06/16 pp404-413
Volume 15, Number 4, August 2010

Heat Transfer in the Microlayer Under a Bubble During Nucleate Boiling*

David M. Christopher**, ZHANG Lu (张 璐)

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education,
Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

Abstract: Many studies have shown that a very thin liquid microlayer forms under vapor bubbles during nucleate boiling. The heat transfer from the surface to the bubble is then significantly affected by this microlayer and the curved region leading into the microlayer. Various models have been developed to predict the microlayer shape and the heat transfer along the curved interfacial region, but they tend to have inconsistent boundary conditions or unrealistic results. This paper presents a theoretical model to predict the microlayer thickness and the heat transfer rates for a variety of conditions. The results show how the wall superheat, the Hamaker constant, the bubble radius, and the accommodation coefficient at the interface affect the evaporation heat transfer rates and the microlayer shape for a large range of conditions for water and FC 72. The microlayer results are then shown to compare well with predictions made by solving the Navier-Stokes equations in the microlayer.

Key words: nucleate boiling; bubble growth; heat transfer; microlayer

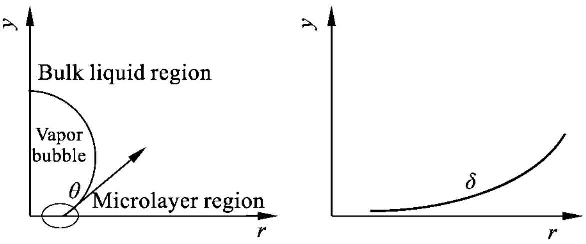
Introduction

The microlayer model introduced by Moore and Mesler[1], Labunstov[2], and Cooper and Lloyd[3] and shown in Fig. 1 has been used to explain bubble growth and the evaporation heat transfer into a vapor bubble on a heated surface during heterogeneous nucleate boiling. Moore and Mesler[1] estimated the microlayer thickness to be about 2 μm. The microlayer characteristics have also been investigated by Wayner and his colleagues[4-6] in a system having an artificial microlayer without a vapor bubble. The microlayer underneath a vapor bubble extends from an arbitrary boundary where it merges continuously into the macro liquid region at a large radius and a relatively large microlayer thickness as shown in Fig. 1b to a very thin layer at smaller distances from the bubble centerline. The heat flux across the microlayer is very large for thin microlayers that are still somewhat larger than the minimum thickness, contributing most of the evaporation into the vapor bubble that drives the bubble growth. Near the bubble centerline, the heat flux decreases to zero as the microlayer reaches an equilibrium thickness as the liquid no longer evaporates because the liquid molecules very close to the wall are kept from leaving the interface by the disjoining pressure that is related to the van der Walls force and other short range forces. The heat flux is then zero even though the microlayer is superheated to the same temperature as the wall. These equilibrium microlayers are typically 5 to 30 nm thick[5,6] depending on the fluid properties and the wall superheat, which is the temperature difference between the wall and the liquid saturation temperature at the system pressure.

Received: 2010-04-07; revised: 2010-06-06

* Supported by the National Natural Science Foundation of China (Nos. 50876050 and 50636030)

** To whom correspondence should be addressed.
E-mail: dmc@tsinghua.edu.cn; Tel: 86-10-62772986



(a) Macro model (b) Microlayer model

Fig. 1 Sketch of microlayer model

There have been a variety of models presented to model the flow and heat transfer in the microlayer. These models also predict the microlayer thickness variation in the radial direction as part of the solution. DasGupta et al.[5,6] compared measured thicknesses of extended meniscuses (an artificial evaporating microlayer without a vapor bubble) at very low heat fluxes with a model based on the Kelvin-Clapeyron equation modeling the evaporation mass flux as a function of the temperature and pressure jumps at the interface with a modified form of the augmented Young-LaPlace equation for the liquid pressure along with the lubrication flow model for the momentum equation. They only gave experimental and theoretical results for very small superheats. Li et al.[7] measured microlayer thicknesses under sliding bubbles in the range of 30-50 μm thick for bubbles sliding along an inclined plate. Hollingsworth et al.[8] then modeled those results using a model based on an assumed velocity distribution in the microlayer and experimentally related models of the heat flux distribution in the microlayer. They also presented a microlayer model based on lubrication theory that did not include the curvature effects or the disjoining pressure effects since their microlayers were relatively thick. Dhir and his colleagues modeled the microlayer in a series of papers (e.g., Refs. [9-11]) by also using the Young-LaPlace equation with lubrication theory, but using the kinetic theory of gases with the Clausius-Clapeyron equation to model the evaporation rate from the interface. They used their model to predict various bubble dynamics but did not give any specific results for the microlayer. Ma et al.[12] calculated the microlayer thickness profiles by approximating the velocity profile in the Cartesian coordinates momentum equation with an average velocity with the fully developed friction factor for flow between parallel plates used for the shear stress on the solid wall. They again only gave results for very small superheats. Mirzamoghadam and Catton[13] used an integral momentum equation approach to predict the microlayer profile and the heat transfer across the microlayer on inclined plates; however, their solution was unstable for many conditions so they could only get stable profiles for specific plate angles and very small wall superheats.

Park et al.[14] analyzed the flow and heat transfer in microlayers in very small channels where the interface shape is constrained by the channel size rather than the bubble size to show the effects of channel sizes on the order of 150 μm. They assumed a constant heat flux which greatly simplified the problem and noted that the Knudsen number in the microlayer is still very small so the Navier-Stokes equations are appropriate. Wang et al.[15] also analyzed the flow and heat transfer in microlayers in very small channels to show that the channel size had very little effect on the heat transfer and microlayer profile. Zhao et al.[16] then analyzed the effects of the Kapitza resistance, slip, and liquid layering on the temperature fields in a microlayer.

In this paper, the model used by Son et al.[10] is further developed into a system of equations that are more stable with boundary conditions that are more consistent with the physics. The model gives stable results over a wide range of conditions. The model is used to analyze the microlayer properties for a range of conditions including the effect of the Hamaker constant which is related to the fluid and solid properties, the bubble size, the superheat, and the accommodation coefficient for the evaporation at the liquid-vapor interface. The results are then compared to a computational fluid dynamics (CFD) solution of the Navier-Stokes equations to verify the validity of the assumptions in the microlayer model.

1 Theory

1.1 Microlayer model

The heat transfer and the flow field in a microlayer under a bubble during nucleate boiling can be predicted along with the microlayer shape by solving the momentum and energy equations within the microlayer[9]. This analysis assumes that the conditions in the microlayer can be represented by steady-state, laminar flow equations. The analysis also assumes that the layer is thin relative to its length and that the liquid