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A compound thermodynamic model for transient bubble growth in microscale

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ABSTRACT

Based upon the classical bubble dynamics, a new compound thermodynamics model coupling with heat transfer mechanism for the bubble growth and collapse during explosive boiling under pulsed heating is presented from a hydrodynamic and thermodynamic perspective. The highlight in this analysis is that the relationship between the variation of the vapor temperature and the vapor pressure inside of a bubble satisfies the conditions of a polytropic process. With a selected compound polytropic index (CPI) and a determined vapor temperature variation for each different stage during the entire bubble evolution under pulsed heating, the bubble behavior can be described and predicted quite well when compared to the experimental observations for pulse ranges.

For the first time, this model reveals the vapor pressure and temperature variation occurring during the bubble evolution and provides an in-depth understanding and insight into the bubble dynamics under pulsed heating. The thermodynamics analysis provides a first order solution to guide future thermal bubble MEMS design.

1. Introduction

Bubble nucleation and bubble growth on a microheater under pulsed heating has been used widely in ink jet printers, biochips and other thermal micro-electro-mechanical systems (MEMS) [1–3]. The vapor bubble growth in these types of boiling systems is a complicated phenomenon involving the heat and mass transfer between the two phases and the heat transfer as outlined in Fig. 1. As indicated, the mathematical description of this physical system is quite complicated. The shape, along with the growth and collapse of the bubble are currently not well understood due to so many factors that affect the bubble behavior. For this reason, previous investigations of these phenomena [1,4,5], have utilized a number of assumptions to reduce the difficulties associated with accurately describing the situation mathematically, and then solving the resulting expressions, e.g., an arbitrary initial bubble size, arbitrarily adjusted boundary conditions (temperature and heat flux) at the interface. The failure to include the nonequilibrium conditions inside the vapor bubble (mechanical, thermal and/or chemical) with respect to the surrounding environment, have made those models circumspect. Mei et al. [6] considered the simultaneous spatial and temporal temperature changes of the heating surface. In their analysis with a heat diffusion-controlled model, however, the effects of the hydrodynamics were not included, resulting in a bubble growth rate that was related to the temperature field around the bubble by the simultaneous energy transfer between the bubble, liquid microlayer and the heating surface alone. There were also several limited direct numerical simulation works on transient bubble growth and collapse under pulsed heating [7–9], however, too many assumptions which were proposed before the simulations made the methods and the results unacceptable beyond their cases. On the other hand, a practical, easy to use and accurate mathematical model is needed for such thermal MEMS design.

In microscale explosive boiling induced by a pulsed laser, rapid electrical pulse, or other high energy mechanisms, the bulk liquid is typically subcooled, i.e., at room temperature, but the temperature of the heating surface will be close to the superheat limit of the liquid. Thus the difference in temperature within the liquid is very large. Fig. 2 presents a result that typifies the temperature distribution in the region surrounding a microheater with a size of $100 \times 100\ \mu m$, following a $15M\ W/m^2$ electrical pulse of approximately 10 ms duration, with no phase change (the numerical model is detailed in Appendix A).

Because of high non-uniform temperature distribution around the vapor bubble for an explosive boiling situation under pulsed heating, the analytical expression for the asymptotic growth of a spherical bubble placed in a uniformly superheated bulk liquid as

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Nomenclature

A	area of the heating surface
C_p	specific heat at constant pressure
C_v	specific heat at constant volume
C_n	specific heat for a polytropic process
E_{cv}	internal energy of the vapor phase inside a bubble
h	specific enthalpy
h_{fg}	latent heat
J	nucleation rate
m	mass
n	polytropic index
N	number of bubble nuclei
p	pressure
p'_v	nonequilibrium vapor pressure
q_w	heat flux
Q	heat energy
R	bubble radius
$\dot{R}$	velocity of bubble interface
$\ddot{R}$	acceleration of bubble interface
R_m	vapor constant
s	specific entropy
T	temperature
t	time
u, v, w	velocity
V	volume of the bubble
W	work

Greek symbols

ρ	density
σ	surface stress
λ	heat conductivity
μ	chemical potential
ν	kinetic viscosity
τ_p	pulse duration

Subscripts

c	critical
co	coalescence
e	equilibrium
h	heater
het	heterogeneous
ne	nonequilibrium
l	liquid phase
s	saturation
v	vapor phase

developed by Plesset and Zwick [10] is not appropriate for this situation.

To date, the interaction between the transient temperature variation of the heating surface and the bubble dynamics have not been considered in the modeling of bubble growth and collapse during the explosive boiling induced by pulsed heating. Based upon the preceding discussions and the literature review, it is assumed that during the transient high heat flux heating on a smooth surface commonly in MEMS, the bubble shape will take the form as shown in Fig. 3(a) rather than Fig. 3(b) from a cavity. Nevertheless, with the fast growth of the bubble that accompanies high power pulse heating, the internal stresses i.e., the hydrodynamic resistance and the pumping force against the wall, will reshape the bubble at the base and will generate a small wedge around the periphery of the bubble base. To determine the accuracy of this hypothesis, using a dark field microscopic top view of the bubble, the presence of this wedge can be clearly seen as shown in Fig. 3(c).

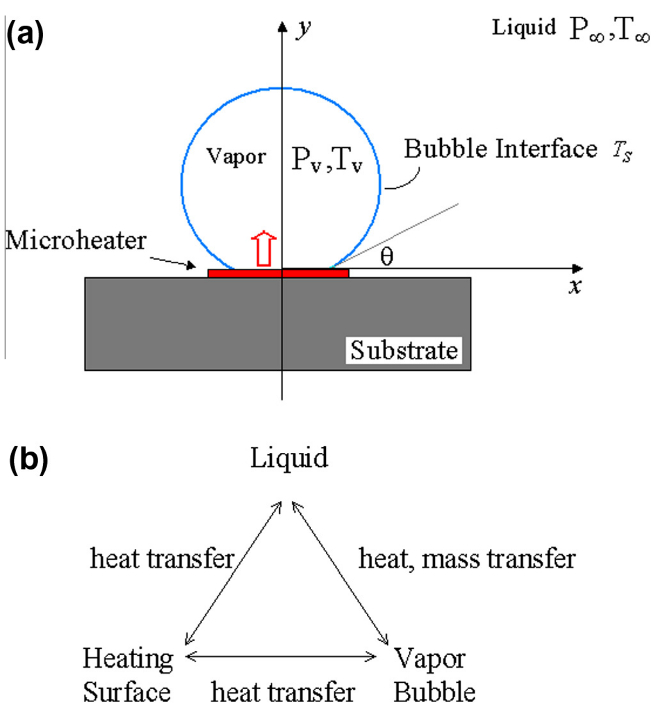

Fig. 1. Schematic heat and mass transfer among two phases and the heating surface.

As discussed above, it is clear that the conditions of the vapor inside a rapidly growing bubble induced by pulsed heating on a flat surface have not been properly formulated in previous investigations. Based upon the classical bubble dynamics and nonequilibrium thermodynamics, in this work, a novel compound thermodynamic model is developed, which encompasses the processes from bubble nucleation and coalescence to bubble growth and collapse under pulsed heating conditions. The thermodynamic analysis herein incorporates the variations occurring in the vapor phase, while considering the heat and mass transfer at the interface of the bubble and the influence of the heating surface on the vapor temperature, with particular attention to the resulting explosive boiling. This model is based on the first and second law of the thermodynamics, with only minimal assumptions required as a result of the different heating conditions and is therefore able to predict the bubble growth and collapse for different heating processes in principle. The calculated results obtained using this model are compared with experimental observations, and are shown to be in good agreement in terms of both the values and the trends.

2. Development of the transient bubble dynamics model

In the current investigation, firstly, the author focuses on the initial stage of bubble nuclei formation and coalesces; secondly, the