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UNDERSTANDING BUBBLE GROWTH MECHANISM(S) OF HIGH VOLATILE FLUID USING ADVANCED GRAIDENTS-BASED DIAGNOSTICS

Alok Kumar[1*], Atul Srivastava[1]

[1]Department of Mechanical Engineering, IIT Bombay, Powai-40076, India

1. ABSTRACT

This study investigates the plausible growth mechanism(s) and dynamical parameters of single vapor bubble during nucleate boiling regime of high volatile fluids under varying subcooling conditions. Dichloromethane (DCM) has been chosen as the high volatile fluid in the boiling experiments. The plausible bubble base growth mechanism(s), microlayer and/or contact line evaporation and the dynamical parameters of the vapor bubbles have been mapped through simultaneous application of thin film interferometry and high-speed rainbow schlieren deflectometry. The experimental observations reveal that unlike conventional fluids, like water, DCM displays a bubble base growth mechanism that is primarily dominated by contact line evaporation and thermal diffusion effects across the superheated thermal layer enveloping the growing vapor bubble. Irrespective of the surface wettability, no distinct microlayer could be observed beneath the growing DCM vapor bubble through thin film interferometry observations. Detailed force balance analysis shows a transition from downward to upward forces facilitating bubble departure beyond 0.9 departure time (t_d).

2. INTRODUCTION

In recent years, the semiconductor industry has seen increased heat generation from electronic devices, surpassing the capabilities of traditional cooling methods based on single-phase heat transfer. Compact electronic systems demand alternative cooling techniques, with two-phase heat transfer, especially pool boiling, gaining attention for its high heat dissipation rates and compactness. Critical heat flux (CHF) is pivotal in determining the safety and efficiency of cooling systems. Employing high volatile dielectric liquids enhances heat transfer efficiency, particularly for electronics operating at temperatures (~ 40 – 50 °C). Despite extensive study on water boiling, dynamics and mechanisms of high volatile liquid boiling remain underexplored. Mechanistic models, like the force balance analysis, have been formulated to understand bubble dynamics, with a focus on surface modifications to enhance nucleate boiling heat transfer. However, spatio-temporal variation in vapor bubble dynamics and underlying forces remain largely unexplored. Dichloromethane (DCM) presents a unique yet underexplored candidate due to its properties. This study aims to comprehensively investigate DCM boiling dynamics, bubble growth mechanisms, and heat transfer for optimization of cooling systems in diverse industrial applications. Through experimental investigations and force balance analysis, this research aims to elucidate fundamental principles governing DCM bubble dynamics, contributing to heat transfer and fluid dynamics knowledge and optimizing cooling solutions for industrial processes dealing with high volatile fluids.

3. METHDOLOGY

This section delineates the methodology employed to analyze bubble dynamics from inception to departure using schlieren and interferometry images. Following the method outlined by Bucci et al. [1], the force acting on the nucleating bubble is calculated. The "equivalent radius" of the vapor bubble, as referenced in [2], is computed by treating it as a sphere with equivalent volume. Assuming axisymmetric in the schlieren image, the vapor bubble's

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*Corresponding Author: alokraj956@gmail.com

volume is determined, treating it as a stack of circular discs, and the instantaneous volume is calculated using specific equations. The base radius, known as the contact radius, is derived from interferograms. Dynamic contact angle measurement is conducted using MATLAB, analyzing four points in the grey scale image. Uncertainty in heat flux measurement is determined considering factors like substrate thermal conductivity and ITO coating area. The location of the dry-patch introduces errors in contact line radius measurement, with a maximum uncertainty of one pixel. The associated bubble diameter is determined with a maximum uncertainty of around 20 µm. These uncertainties represent the highest standard deviation obtained through the masking technique applied to the bubble's outer boundary and base radius region.

4. RESULTS

This section presents the results of an experimental investigation into the formation and growth of single vapor bubbles at a heat flux of 95 kW/m² and three different subcooling levels (0, 2, 4°C) of dichloromethane (DCM) on an indium-tin-oxide (ITO) coated borofloat glass surface. The thermophysical properties of DCM are referenced from [3]. Various dynamic parameters and forces, such as buoyancy, contact pressure, surface tension, and growth forces, were analyzed. Figure 1 illustrates the nucleate boiling process from initial nucleation to bubble departure, featuring rainbow schlieren images of bubble growth and interferometry images of the dry patch and base diameter evolution. Notably, no detectable microlayer was observed for DCM bubbles, unlike conventional fluids like water, which typically form a microlayer. This is due to DCM's high volatility, leading to rapid evaporation and dry patch formation. The contact area beneath the growing vapor bubble is crucial for understanding microlayer evaporation and surface tension forces. However, tracking the three-phase contact line precisely with high-speed side-view cameras is challenging. To overcome this, the thin film interferometry image was used to detect the base diameter. In the present case where the microlayer is notably absent, the dry patch is considered as the bubble's contact line radius.

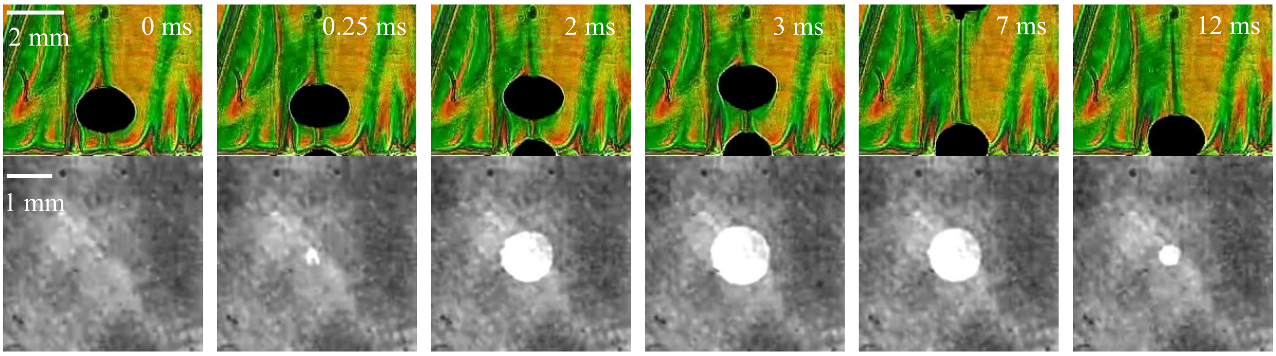

Fig. 1 Images of isolated vapor bubble during a complete ebullition cycle of DCM captured using rainbow schlieren and thin film interferometry

The dynamics of bubble departure are influenced by a balance of physical forces like surface tension and buoyancy, and fluid properties including viscosity and thermal conductivity. Bubble departure diameter depends on the interplay of these forces and the bubble's growth rate and shape. The equivalent bubble diameter calculated based on total bubble volume, and its temporal evolution are shown in Figure 2 for different subcooling levels. The bubble growth process is divided into three phases: initial (inertia-controlled growth), transitional, and diffusion-controlled expansion, with heat flux increasing the equivalent radius of the bubble prior to departure. In the initial growth phase, characterized by inertia-controlled growth, rapid expansion occurs. Transitioning into the transitional regime, the growth rate slows, and in the diffusion-controlled expansion phase, growth becomes minimal, requiring the most time for significant expansion. The slope of the non-dimensional curve remains consistent across different subcooling levels, suggesting a stable relationship between subcooling and bubble growth dynamics.

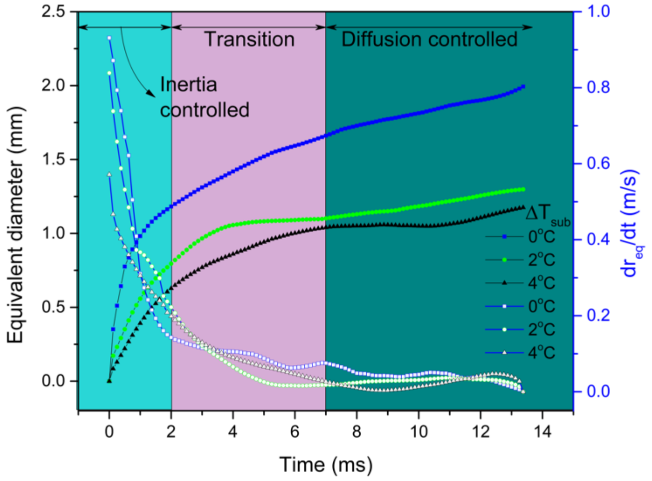

Fig. 2 Equivalent diameter and growth rate of DCM bubble as a function of subcooling at 95kW/m^2

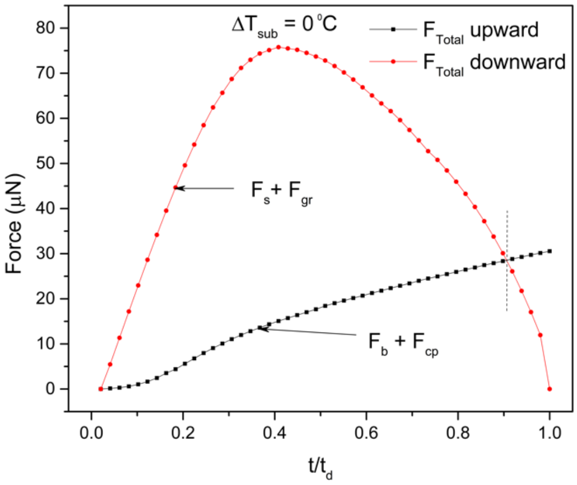

Fig. 3 Temporal evolution of total upward and total downward forces acting on the bubble

Figure 3 represents the total upward and downward forces acting on the bubble at a heat flux of 95 kW/m². Both forces are plotted positively for easier comparison, despite the downward force (surface tension and growth force) acting oppositely. This unconventional representation allows a more intuitive comparison of their magnitudes and variations. Initially, the downward force on the bubble is high, peaking around 75 µN at a t/t_d ratio of 0.4 before gradually decreasing to zero. Throughout the evolution up to $t/t_d = 0.9$, the downward force consistently surpasses the upward force, promoting bubble growth and suppressing departure. Equilibrium is reached around $t/t_d = 0.9$ (indicated by a dotted line), where the forces balance. Subsequently, at t/td > 0.9, the upward force dominates, facilitating bubble departure from the surface.

5. CONCLUSIONS

This experimental study delves into the boiling behavior of high-volatile fluids, focusing on dichloromethane (DCM) on an indium-tin-oxide (ITO) coated borofloat glass surface. Surprisingly, DCM exhibits a bubble formation mechanism without a microlayer, contrary to conventional fluids like water. This absence of a microlayer is attributed to DCM's high volatility, which hampers microlayer formation due to rapid evaporation. The temporal evolution of DCM bubble dynamics under different subcooling reveals distinct growth phases: inertia-controlled growth, transitional regime, and diffusion-controlled expansion. Analysis of force balance throughout the process highlights the dominance of downward forces until 0.9 departure time (t_d), promoting growth and inhibiting departure, with upward forces taking over thereafter, aiding detachment. This study not only advances heat transfer and fluid dynamics knowledge but also offers practical insights for optimizing cooling systems in industries using high-volatile fluids as coolants. It underscores the importance of further research into the boiling behavior of such liquids.

REFERENCES

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