Origin of Microlayer in Pool Boiling

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Primary CNF Tools Used: CHA thermal evaporator, E-beam evaporator, CVC sputter, Oxford PECVD, GSI PECVD, Glen 1000 Plasma, Oxford 81/82 etcher

Abstract:

Microlayer evaporation is one of the major heat transfer mechanisms of boiling. In our work, the microlayer thin film is visualized *in situ* in a vapor bubble during pool boiling. Contrary to current understanding, bubbles originate on hydrophilic and silane-coated hydrophobic surfaces without a three-phase contact line, i.e. the microlayer completely covers the bubble base. The occurrence of such a wetted bubble base is found to be dependent on the liquid-solid interaction, which is validated by molecular dynamics simulations of nucleation of liquid argon on hydrophilic and/or single-layer hydrophobic atoms on hydrophilic surfaces. The work reported here is part of a journal article which is currently under review.

Summary of Research:

Microlayer is a thin liquid film trapped underneath a vapor bubble next to three-phase contact line. The base of the bubble can be divided into three regions: nanoscale non-evaporating film region, microscale evaporating film region, and millimeter scale bulk meniscus (Figure 1). Extremely high heat flux occurs in the microlayer region due to its low thermal resistance, which is proportional to liquid layer thickness. Microlayer evaporation serves as one of the major heat transfer mechanism. Better understanding of the microlayer has led to novel approaches for boiling heat transfer enhancement: microstructures fabricated on pool boiling surface causes early evaporation of microlayer, resulting in ~ 120% enhancement in the critical heat flux [1]. In our work, we studied origin of microlayer by *in situ* visualizing the microlayer in a vapor bubble in pool boiling, and performing molecular dynamics simulations of bubble nucleation.

We used laser heating to create a vapor bubble on a surface submerged in a pool of deionized (DI) water at room temperature. The surface consists of several metal layers for laser heating technology (Figure 2): a 40 nm thick tungsten was deposited on a glass substrate to absorb the laser and heat the surface; a 1 μm thick PECVD SiO_2 was deposited to serve as hydrophilic surface (contact angle: $33.4 \pm 2.7°$); two 10 nm thick Ti layers were deposited acting as adhesion layer. To form the vapor bubble, a blue CW laser beam (wavelength of 447 $\pm$ 5 nm) was introduced into an inverted microscope, passed through a 50× objective, and focused on the sample to generate a highly localized heating area corresponding to an equivalent beam diameter of ~ 15 μm. The same objective was used to image the bubble which was illuminated from above with a 632 nm HeNe laser. This configuration creates a bubble image with a dark annulus ring as light has to refract across multiple interfaces in that region. A high-speed camera was used to record the bubble formation process.
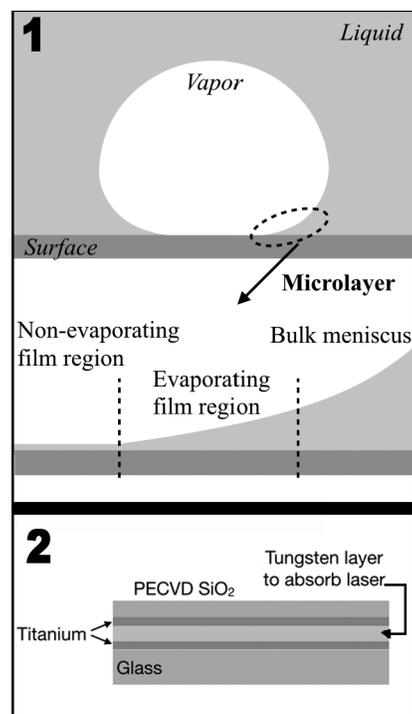
Figure 1, top: Microlayer underneath a vapor bubble in pool boiling. Figure 2, bottom: Sample surface with metal layers to absorb laser.

The microlayer is *in situ* visualized using this setup because fringes would be observed in microlayer region. These fringes were observed due to thin film interference of monochromatic incident light with partially reflected light within the thin liquid microlayer. As the generated dark and bright fringes correspond to constructive and destructive interference respectively, these fringes are separated by an optical path difference which is half wavelength, and the position of the fringes can be used to build microlayer profile.

In our experiments, the fringes are surprisingly seen throughout the bubble base on the surface, indicating that the microlayer liquid film covers entire bubble base and no three-phase contact line forms (Figure 3). In order to understand the physics behind the completely wetted bubble base, molecular dynamics simulations were performed in LAMMPS [2] software with liquid argon present between two walls. The upper wall was moved outward at a certain speed to decrease the pressure in the liquid and initiate nucleation. The lower wall was modeled as the hydrophilic surface by using a 12-2 Lennard Jones potential between the wall and argon atoms. Similar to the experiments, a liquid film is present between the bubble and the surface (Figure 4). Statistical analysis from molecular dynamics simulation shows that due to the strong interaction between the hydrophilic wall and argon atoms, high density liquid layers form near the wall, leading to significantly high pressure in that region. Thus, a bubble forms above these liquid layers as it is thermodynamically favorable to achieve lower pressures required for nucleation, resulting in a liquid film being present underneath the bubble. This mechanism can be amplified / weakened with different wall-liquid combinations, for e.g., interaction between SiO_2 and water were much stronger as polar atoms are involved, leading to thicker high-density liquid water film that is measurable in experiments. However, the completely wetted bubble base will not likely be observed on weak interacted wall-liquid combinations (if either is non-polar).

In summary, we observed that the bubble, at its early growth stage, had a bubble base that is completely covered by the microlayer; similar observation was found in molecular dynamics simulations. This entirely wetted bubble base is due to the strong wall-liquid interactions, the thickness of microlayer is determined by the wall-liquid interactions.

References:

[1]   A. Zou, D. P. Singh, and S. C. Maroo, Langmuir 32, 10808-10814 (2016).

[2]   S. Plimpton, J. Comput. Phys. 117, 1-19 (1995).

Fringes covers the entire region, indicating completely wetted bubble base
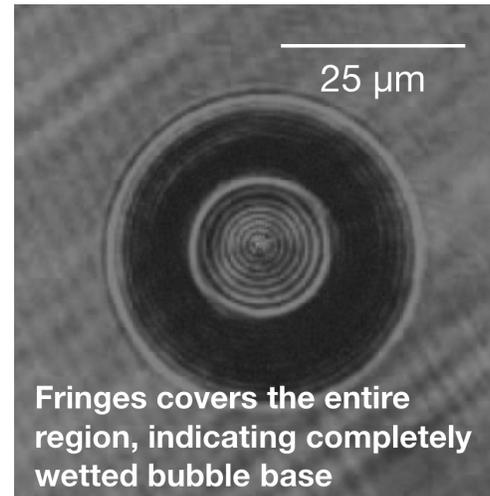
Figure 3: Image of a vapor bubble with completely wetted bubble base.
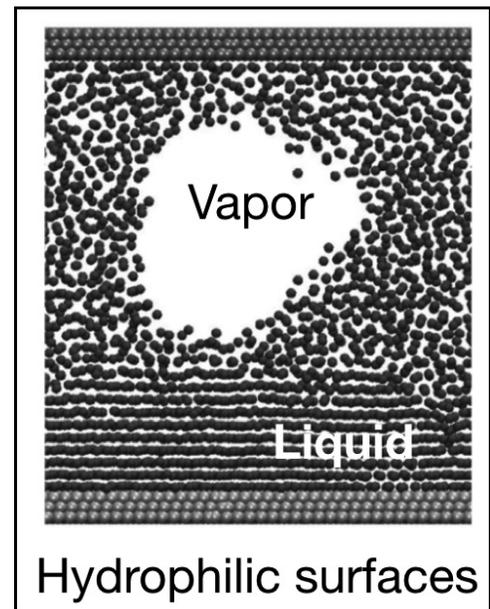
Figure 4: Bubble with completely wetted base in molecular dynamics simulation.