Pool Boiling Critical Heat Flux Enhancement by Early Evaporation of Microlayer

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Abstract:
Microlayer evaporation is one of the major heat transfer mechanisms of boiling. In our work, the boiling heat transfer is enhanced by affecting microlayer evaporation. The microlayer evaporates sooner due to the presence of ridges of a few micrometer high, leading to the increase in bubble growth rate, heat transfer, departure frequency, and critical heat flux. Approximately 120% enhancement of critical heat flux is obtained with only ~18% increase in area. This new mechanism is validated by comparing the growth rate of a laser created bubble on a ridge-structured surface and a plain surface, and the corresponding prediction of the critical heat flux is found to be in good agreement with the experimental boiling data. This work was published in Langmuir in 2016 [1].

Summary of Research:
Boiling has been widely used in industry as it utilizes the high latent heat of vaporization of a liquid to transfer large amounts of heat over a small surface area. Boiling occurs due to the heterogeneous nucleation and growth of vapor bubbles. Increasing the heat flux leads to more rapid formation and coalescence of the bubbles, an operation limit is reached when the bubble generation rate overcomes its removal rate, causing a vapor film to cover the surface. This limit, which is known as the critical heat flux (CHF), determines the highest heat flux that can be reached by pool boiling. CHF causes a drastic increase in surface temperature as the heat cannot be removed by the liquid due to the insulating vapor film. Thus, enhanced CHF is extremely demanding as high heat flux removal is required to achieve next generation energy and electronic devices.

Microlayer is a thin liquid film trapped underneath the vapor bubble. Microlayer evaporation is one of the major heat transfer mechanisms in boiling. The heat transfer rate in the microlayer region was identified as 1-2 orders higher than the overall value [2]. Thus, affecting microlayer evaporation to enhance boiling heat transfer performance becomes attractive. In our work, we utilized ridges with a few micrometer high to partition the microlayer into to water slabs and to disconnect it from the bulk liquid. The separation of the microlayer leads to an increase in its energy, thus causing it to evaporate due to the higher surface temperature. Compared to a plain surface, the microlayer evaporates sooner on a ridge-structured surface, resulting in an increase in bubble growth rate, bubble departure frequency and therefore critical heat flux.

The ridges were fabricated on the top surface of a Si substrate by deep ultraviolet photolithography, followed by plasma etching. A 125 nm thick thermal oxide layer was subsequently grown to achieve SiO2

Figure 1: SEM image of ridges.
ridges. A thin film of indium tin oxide (ITO) was deposited on the back side of the wafer by physical vapor deposition, and served as the heater. Copper electrodes were patterned on the ITO using chemical vapor deposition. The wafer was diced into 2 cm × 2 cm sample. Figure 1 shows the images of ridges using scanning electron microscopy. In boiling experiments, the sample was attached on top of a polycarbonate holder located inside a liquid chamber and immersed in a pool of deionized water. The water was degassed by boiling it for one hour. After degassing, the water was maintained at saturation conditions during the experiments. Boiling on the sample was achieved by supplying power to ITO heater. The temperature of the ITO heater was measured by a T-type thermocouple. CHF was obtained when an incremental increase in the power resulted in a sudden and dramatic increase of the heater temperature.

Figure 2 shows the boiling curves for plain SiO₂ and ridge-structured surfaces. A boiling curve is a plot of heat flux versus superheat, which is defined as temperature difference between the surface and the saturated liquid. 177.2 ± 3.3 W/cm² of CHF was achieved on a ridge-structured surface, which is ~120% enhancement with only ~18% increase in surface area compared to a plain surface (78.8 ± 1.6 W/cm²). Considering the heat flux based on the wetted area, 62% enhancement in CHF was attained, which is one of the highest values among reported values in literature (Figure 3) [3, 4].

To verify the early evaporation of the microlayer with independent experimental data, the growth rate of a vapor bubble is measured on a ridge-structured surface and a plain surface. As mentioned above, the early evaporation of the microlayer is expected to increase the bubble growth rate and thus the bubble departure frequency, leading to CHF enhancement. As shown in Figure 4, the bubble growth rate is ~5.25 times faster on the ridge-structured surface than on the plain surface. According to Mikic’s model [5], the CHF on the ridge-structured surface will be enhanced by 1.80 to 2.24 times that on a plain surface, which is in very good agreement with the CHF increase of 2.19 times achieved in boiling experiments.

In summary, we reported a new boiling heat transfer mechanism, which is early evaporation of the microlayer due to the presence of ridges, and this new mechanism was validated by independent experimental data of the growth rate of the laser created bubble.

References: