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WETTING DYNAMICS OF A DROPLET ON A SUPERHEATED SURFACE

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Leidenfrost boiling, droplet impact, electronic cooling, wetting

ABSTRACT

Understanding the dynamics of drop impact on a heated surface is crucial for thermal management of electronics[1], [2]. It is important to experimentally capture the temperature field underneath the impact area during the impingement. Concomitantly, it is desirable to visualize the dynamic wetting during the course of impact so that comprehensive thermo-fluidic details of the process could be discerned. Several interesting experimental approaches have been discussed in literature to capture the temperature field such as using IR (infrared)-opaque platinum film on transparent sapphire or directly recording the liquid temperature using LIF (laser induced fluorescence)[3]–[5]. On the other hand, optical techniques such as total internal reflection (TIR) and interference have been deployed for elucidating triple contact point dynamics during the course of drop-substrate interaction[6]–[9]. What has not been addressed in these reports is the quantification of the droplet wetting geometry as a function of superheat where superheat refers to difference between surface temperature and boiling temperature of working fluid. Figure 1 shows the experimental setup we are working with for investigating the droplet wetting dynamics using TIR. Simultaneous TIR and IR studies can be performed using our setup as the sapphire and ITO are both optically transparent. The aim of this study is to calculate the area and perimeter of contact seen as a function of superheating with the TIR setup shown in Figure 1.

The experiments were performed with ~2mm diameter ethanol drop (density, ρ ~ 780Kg/m^3) impinging at a We ~50 (Weber Number - $\frac{\rho v^2 d}{\sigma}$, where ρ is density, $v = \sqrt{2gh}$ is impact velocity, g ~ 9.8m/s^2, h is impact height, d is diameter and σ is surface tension). The images were captured with Phantom v311 high speed camera and temperature was recorded off a black tape (3M, emissivity ~0.96) on the top ITO (Indium-Tin Oxide) surface using FLIR SC5600 thermal camera. The high speed camera pixel intensity changes to black from white as droplet wets the surface, as shown schematically in Figure 1. The ITO is Joule heated using a power supply. The captured images were post processed in ImageJ/MATLAB to calculate the area and perimeter of observed wetting. The area corresponds to number of pixels in captured image, while perimeter corresponds to number of boundary pixels.

Figure 2 shows the results of area and perimeter of wetting observed underneath 2mm ethanol drop at We~50 using TIR. Three inset figures illustrate typical contact observed with TIR in contact, nucleate and Leidenfrost regimes in the order of increasing superheat. We found contact area decreasing non- monotonically with the

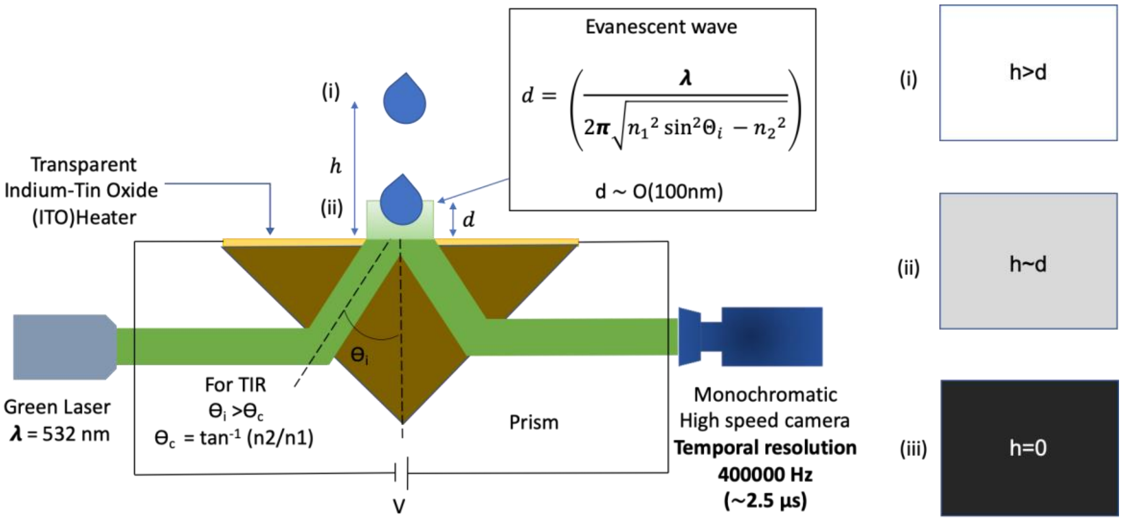

Figure 1. *Schematics of TIR experimental setup used for investigating the drop impact on heated surface*

increase in surface superheating. At low superheating, the contact area approximates the value of the area of a circle, while increase the extent of superheating allows the formation of vapour bubbles which leads to decrease in liquid wetting during nucleate boiling. We found that, in contact boiling regime the contact area remains approximately constant up to superheating (37 K), while it decreases sharply with increase in temperature during nucleate boiling regime (37-77K). We found that droplet bounces off the surface at superheating of 77K despite some contact seen with TIR, which is interesting given the conventional notion that bouncing on heated surfaces is preceded by a formation of a vapor layer. Further, we found that in the bouncing regime no more contact is observed as we approach the superheating of about 97K.

We calculated the perimeter of these experimentally captured wetting and results are presented on same ordinate as area in Figure 2 in units of camera pixel. The perimeter remained approximately constant and

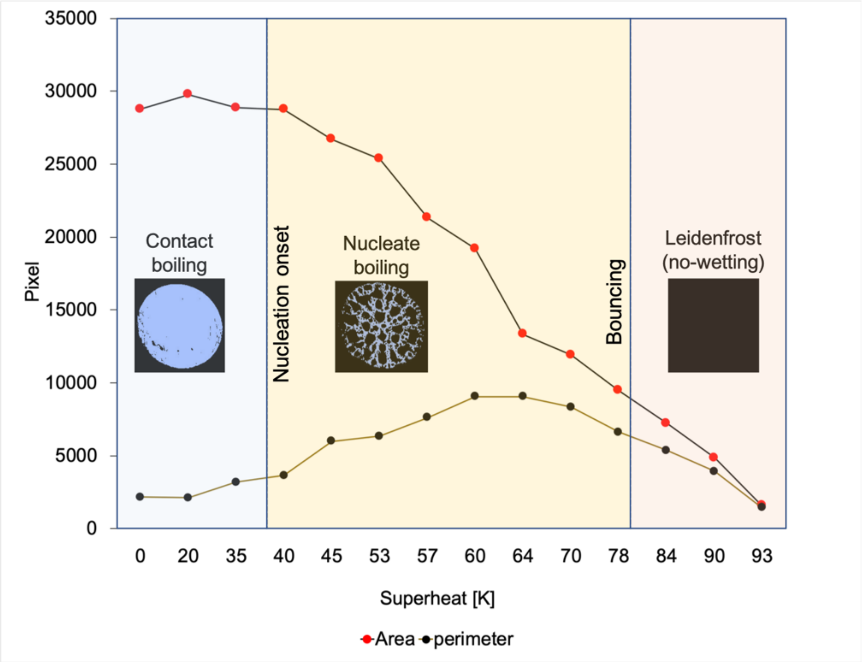

Figure 2: *Area(A) and perimeter(P) of wetting observed on heated surface upon drop impact as a function of superheating. Blue pixels in inset figures is wetted region.*

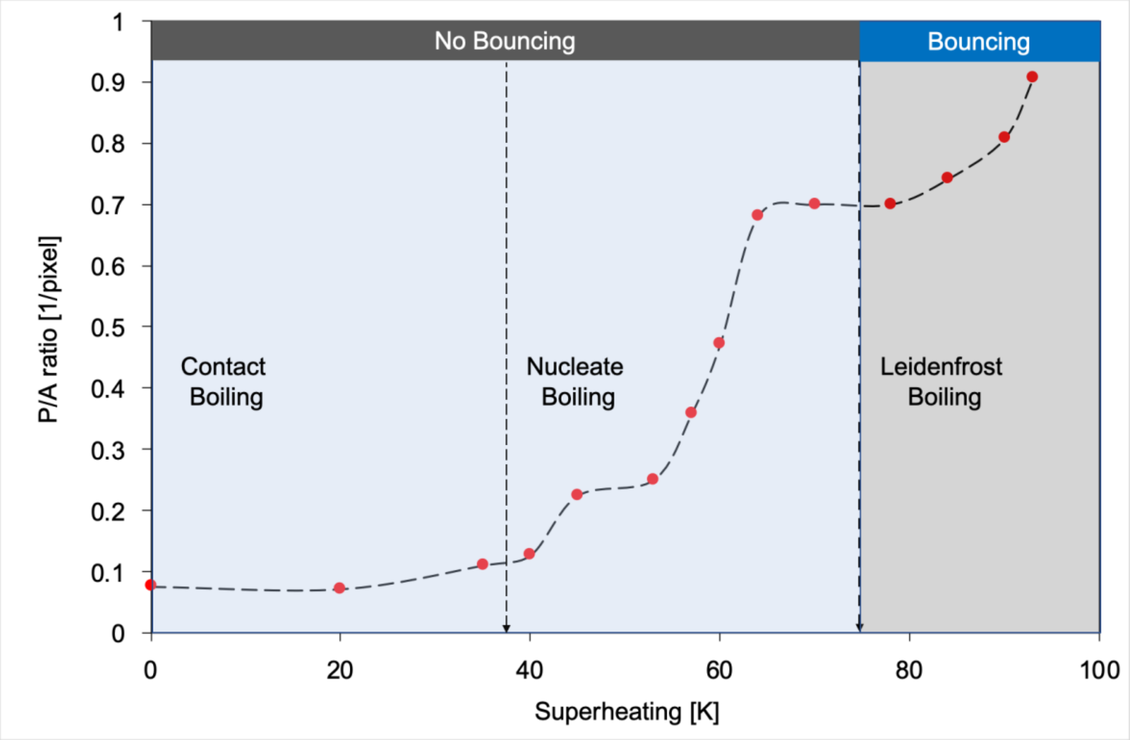

Figure 3. *Plot of P/A ratio of wetting geometry as a function of superheating*

equivalent to the perimeter of a circle up to a certain superheating, however it increases in nucleate boiling regime and then decreases as we move away from nucleate boiling into bouncing regime.

Figure 3 shows the numerical value of P/A ratio plotted as a function of superheating, it was found that P/A ratio increases monotonically in contrast to non-monotonic behavior of area and perimeter with temperature. Although, we don't have a definitive explanation but one can arguably credit this monotonic trend to the decrease in surface tension with temperature. The liquids have a negative temperature dependent surface tension coefficient ~ -0.01mN/m/K, reference being room temperature 298K [10]–[12]. For instance, ethanol has a surface tension of 22.8mN/m at 298K and it reduces to roughly ~6mN/m at 80K superheat [13]. Consequently we can expect interface length per unit area to increase with superheating and hence the trend of P/A ratio monotonically increasing when plotted against superheating on abscissa. Further, one can also argue that large numerical value of P/A is an indicative of instability as the restoring surface tension force decreases with temperature. At this juncture, we can qualitatively propose an answer to the question "what mediates the transition from nucleate to Leidenfrost boiling", it is rather an instability manifested as increase in P/A underlies the transition to Leidenfrost boiling.

Figure 3 also shows that P/A can be used as a single parameter to conveniently differentiate various regimes of boiling. The contact boiling regimes belongs to regime of low value of P/A (<=0.1), while nucleate boiling regime corresponds to moderate value of P/A (0.1-0.7). The Leidenfrost or bouncing regime maps to high value of P/A > 0.7. This quantitative classification scheme is robust compared to schemes used in literature such as secondary atomization as an indicator of Leidenfrost onset, visual inspection/side-view imaging of bouncing and evaporation time (is rather vague and non-monotonic with respect to superheating)[6], [14], [15].

The paper discusses the wetting dynamics of an ethanol droplet on superheated solid surface. We quantified the area and perimeter of contact wetting observed with TIR. It was found that contact area and perimeter varies non-monotonically with superheating. We noted that bouncing on heated surfaces is not necessarily preceded by vapor sandwich up to a certain superheating. The numerical value of perimeter/area of these wetting footprints increases monotonically with the temperature and could be used as a single parameter to classify various regimes of boiling. And, perimeter/area for a bouncing drop is greater than for the case when droplet is undergoing nucleate boiling.

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