Hydrodynamics of droplet impingement on hot surfaces of varying wettability

Cristian E. Clavijo, Julie Crockett *, Daniel Maynes

Mechanical Engineering, BYU, Provo, UT 84602, United States

A B S T R A C T

This work presents on the hydrodynamics of water droplet impingement on superheated solid surfaces across the entire wettability spectrum: superhydrophilic, hydrophilic, hydrophobic and superhydrophobic. While a large body of work exists on droplet impingement on hydrophilic and superhydrophilic surfaces, impingement on the latter two has been largely neglected and the present results show that dynamics are dramatically different. Experiments ranging in surface temperature from 125°C to 415°C and Weber numbers from 10 to 225 were performed and analyzed using high-speed imaging. Some of the most striking differences are as follows. While atomization is always present for impingement on the hydrophilic and superhydrophilic surfaces at temperatures below the Leidenfrost point, atomization is absent at low Weber numbers and at low excess surface temperatures on the hydrophobic surface. At high surface temperatures, the attraction of vapor bubbles on the hydrophobic surface allows a vapor blanket to form more readily thus leading to Leidenfrost behavior at a much lower temperature than classically observed on a hydrophilic surface. One of the most interesting phenomenon that will be discussed includes what will be described as a "pseudo-Leidenfrost" state for impingement on the superhydrophobic surface. Because water can be suspended at the peaks of the roughness on a superhydrophobic interface, vapor escapes from underneath the droplet thus mimicking Leidenfrost behavior for all excess temperatures. This results in minimal atomization for superhydrophobic impingement over the entire regime explored. Finally, maximum spread diameters for Leidenfrost impingement are tabulated as a function of the Weber number for all surfaces and are shown to be larger on the smooth surfaces than on the textured ones indicating that droplet spreading at the Leidenfrost point is *not* independent of surface type as previously supposed.

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1. Introduction

Significant interest in the interaction between droplets and superheated solid surfaces is evident by the plethora of publications in the last few years [1–10]. Droplet impingement is present in a wide array of applications including spray cooling, coating, biochemical reactions and combustion, and is the focus of this paper. The physics involved are rich and complex. From a hydrodynamical standpoint, a droplet impinging a hot surface may boil violently, atomize and splash, or rebound without either splashing or atomizing (or a combination of the two). Instantaneous heat transfer rates correspondingly vary dramatically across these different regimes. While ample research has been performed in this field, most of it has focused on high energy surfaces relative to the liquid (eg. hydrophilic in the case of water) [10–13]. In this work, we explore single droplet impingement on hydrophobic and superhydrophobic surfaces heated above the saturation temperature of the liquid.

Boiling regime maps for water droplet impingement on heated smooth hydrophilic surfaces show contact boiling increases with increasing surface temperature at low excess temperatures [11]. When boiling, a droplet becomes populated with vapor bubbles that can burst and eject tiny droplets into the surrounding gas. The ejection of these tiny droplets is generally referred to as atomization or secondary atomization; we will refer to it as atomization. It is now well established that for relatively high surface temperatures, atomization ceases to occur and the droplet rebounds as if on a superhydrophobic surface, despite the strong liquid-solid attraction. The lack of atomization is attributed to the coalescence of the increasing number of vapor bubbles, which results in a thin vapor film underneath the droplet through which vapor can escape, thus preventing vapor bubbles from forming within the droplet [10–13] and this regime is known as film boiling. The lowest surface temperature at which atomization ceases to occur has been named the Leidenfrost point (LFP)

[14–17]. Tran et al. analyzed film boiling dynamics using an optically-transparent sapphire plate as the impinged surface and observed that the liquid does not contact the solid for impingement during film boiling [12], supporting the theory of a thin vapor film below the droplet and resultant lack of atomization.

A balance between vapor production, associated with the surface temperature, and inertia of the impacting droplet, associated with the Weber number $We = \rho V^2 D / \sigma$ (where ρ, σ, V and D represent liquid density and surface tension, impact velocity and initial diameter, respectively), defines the transition between contact and film boiling. Consequently, this transition temperature (i.e. the LFP) increases with increasing Weber number [10–13]. As surface temperature increases, well above the LFP, an entirely new regime termed "spray film boiling" has been observed on smooth hydrophilic surfaces [12]. We limit the scope of this work to surface temperatures below this regime and therefore no atomization was observed at temperatures above the LFP.

Textured hydrophilic surfaces have been shown to alter vapor generation and vapor flow dynamics below the droplet. Micropillars can decrease the LFP temperature at a given We due to enhanced vapor production [13,18]. To test this hypothesis, Tran et al. showed that as pillar height increases the LFP decreases, supporting the idea that enhanced solid surface area (by texturing) during impingement promotes the formation of the vapor film at a lower temperature [13]. Interestingly, it seems that the very densely packed micropillars can have an opposite effect. Zhang et al. found that the LFP increased for such textured surfaces due to suppressed lateral vapor escape [18], which has also been reported elsewhere [5,19].

The maximum spread diameter, D_{max}, at the LFP provides insight to the dynamics of the system as well and has been explored in multiple previous works [9,20–23]. Tran et al. showed that D_{max} is larger at the LFP on a hydrophilic surface than on a superhydrophobic surface maintained at room temperature for $We < 1000$, although both exhibit similar spreading/retracting dynamics [12]. These trends have also been confirmed elsewhere [24]. Larger maximum spread diameters during Leidenfrost impingement are attributed to droplets being hotter (less viscous) and not interacting with the solid (less frictional resistance). These results seem to indicate that droplet spreading/retracting dynamics in the film boiling regime may be independent of the wettability of the surface since the droplet is suspended above its own vapor with negligible contact with the solid [13].

Though previous research has covered a broad range of experimental conditions and provided great insight into the physics of the interaction between a droplet and a heated hydrophilic surface, impingement on hydrophobic and superhydrophobic surfaces at elevated temperatures has received only modest attention [9,25,26,18]. Park et al. performed experiments of droplets (360 μm in diameter) impinging at $We = 60$ on hydrophilic and hydrophobic surfaces over a temperature range of 110–210°C [26]. However, because the study was mainly focused on thermal transport considerations between solid and droplet, little information on boiling hydrodynamics was provided. They reported that the residence time was generally lower for impingement on a hydrophobic substrate, but no information regarding Leidenfrost transition temperatures or maximum spread diameter at the LFP was given. In a different work, Li et al. reported hydrodynamic behavior of impinging droplets at $We = 22$, such as droplet height, diameter and dynamic contact angles, on surfaces of varying wettability (hydrophilic to superhydrophobic) but the maximum surface temperature explored was limited to 110°C [9]. More recently, Zhang et al. explored impingement on superhydrophobic surfaces with microscale posts in a square lattice [18] for Weber numbers up to 85 and temperatures up to 320°C. They mapped

different behaviors including contact boiling and rebound with and without satellite droplets (at around the LFP). The LFP temperature is lower for droplet impingement on the sparsely spaced micropillars than on the more densely packed micropillars. This can be explained again by a balance of vapor generation and micropillars blocking the vapor flow, which is similar to what occurs on hydrophilic surfaces [18]. For sessile droplets the boiling dynamics on heated superhydrophobic surfaces ($< 230°C$) is minimal relative to hydrophobic surfaces [27]. Additionally, a shift to higher Leidenfrost temperatures for superhydrophobic surfaces relative to smooth hydrophobic [27,28] and superhydrophilic relative to smooth hydrophilic surfaces [29,30] has been observed, but only for static droplet scenarios.

This paper presents on the phenomena of a millimetric water droplet impinging with Weber numbers from 10 to 225 on heated surfaces across the entire wettability spectrum (superhydrophilic to superhydrophobic). The range of surface temperatures explored is 125–415°C. Given that a broad body of work on hydrophilic/superhydrophilic impingement already exists, the main contribution of this work is attributed to dynamics on the hydrophobic and superhydrophobic surfaces. Notwithstanding, experiments were also conducted on hydrophilic and superhydrophilic surfaces for comparison with other works. Section 2 provides a detailed methodology of the experimental approach. In Section 3, high-speed images are provided which qualitatively show the difference in atomization and vapor bubble formation across the different types of surfaces for varying We and surface temperatures. Atomization regime maps are constructed for each surface, which clearly identify the LFP as a function of the Weber number. Maximum spread diameters at the LFP as a function of time and impact Weber number are also provided. Brief conclusions are given in Section 4.

2. Experimental procedure

Four surface types were fabricated on 500 μm thick/100 mm diameter polished silicon wafers: superhydrophilic (SHL), hydrophilic (HL), hydrophobic (HB) and superhydrophobic (SHB). For the HL surface, an unaltered polished silicon wafer was used yielding a static contact angle of $30 \pm 3°$. For the HB surface, a 200 nm coat of Teflon was applied to a wafer in the following manner to render it hydrophobic. Teflon (4, 5-difluoro-2,2-bis(trifluoromethyl)-1,3-dioxole) was dissolved in FC-40 to yield a 0.2% Teflon solution, which was subsequently applied to the wafer by spin coating (a ~ 100 nm chromium layer was applied first for adhesion promotion). The wafer was then placed on a hot plate at 90°C for 5 min, 165°C for 5 min and 330°C for 20 min. Teflon was chosen as the coating material due to its stronger thermal stability than other hydrophobic coats such as organosilanes. The receding and advancing contact angle on the HB surface were 113° and $128 \pm 3°$, respectively. For the SHL and SHB surfaces, wafers were first arrayed with a square lattice arrangement of micro-pillars via photolithography and etching (6 μm diameter, 8 μm height and 16 μm center-to-center spacing). Teflon was applied in a similar manner to the description above to yield the SHB surface, while the SHL surface was left uncoated. Roughness is known to increase hydrophilicity/phobicity on a given surface per the Wenzel and Cassie-Baxter equations [31,32], respectively: $\cos \theta = r \cos \theta_e$ and $\cos \theta = \phi \cos \theta_e + \phi - 1$, where θ, r, θ_e and ϕ respectively represent the apparent contact angle, the overall surface area divided by its projected area (roughness), intrinsic contact angle, and the area of the top of the pillars divided by the projected area of the surface (solid fraction). For the SHB and SHL surfaces $r \approx 1.6$ and $\phi \approx 0.11$. The receding and advancing contact angles on the SHB surface were 145° and $165 \pm 3°$, respectively, while the same angles for the SHL surface were both negligible. SEM images and