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STUDY OF DROPLET IMPACT ON HEATED SURFACES USING TOTAL INTERNAL REFLECTION

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ABSTRACT: The present study reports observations of the instantaneous boiling and spreading behaviors of ethanol droplets impacting on heated glass surface. By using the total internal reflection technique, we obtain the exact contact area between the liquid and the solid surface as the drop spreads out and boils as a function of time. We show that the contact area decreases with increasing temperature due to the formation and growth of vapor bubbles at the liquid-solid interface. The technique is useful for studying phenomena involving droplet-surface interaction, which is crucial in the emerging additive manufacturing technology.

INTRODUCTION

Although the impact of droplets on solid surfaces has been studied for more than a hundred years starting from the pioneering work by Worthington (1876), it is still an active research area as there are many fundamental questions remained to be answered and numerous relevant process in industrial applications. From the fundamental point of view, one of the reasons that makes this problem challenging is the wide range of the parameters that govern the impact outcomes (Yarin (2006)). The long list of these parameters, beside the droplet velocity and size, include the ambient pressure, as well as the properties of the liquid and the substrate such as surface tension, viscosity, density, and surface roughness. From the practical point of view, droplet impact is the core process in many emerging applications such as additive manufacturing of electronics (Torrissi et al. (2012)) using metallic glasses (Ladd et al. (2013), Wang and Wong (2011), Wang and Wong (2012)) and graphene (Torrissi et al. (2012), Wong and Vijayaraghavan (2012a)), spray cooling of heated surfaces fabricated with microstructures (Tran et al. (2013)) or carbon nanotubes (Nair et al. (2014), Vijayaraghavan and Wong (2013), Wong and Vijayaraghavan (2012c) and Wong and Vijayaraghavan (2012b)).

In the case of droplets impacting on superheated surfaces, the heat transfer from the surface to the liquid is of great practical interest. One of the main factors that strongly influence this quantity is the contact area between the liquid and the surface. This contact area is greatly affected by the formation and growth of vapor bubbles at the solid-liquid interface. The very fast dynamics and positions of the vapor bubbles have made measurements of the contact area a particularly challenging task. Hence, in both cases of the impact of droplets on unheated and heated surfaces, it is crucial to obtain the exact values of the contact area between the impinging droplet and the surface.

In this paper, we experimentally investigated the impact of ethanol droplets on unheated and heated glass surfaces by combining high-speed imaging with the total internal reflection (TIR) principle. This method enables us to measure the exact contact area and its temporal dependence for surfaces at different temperatures. This was not possible with the conventional side-view high-speed imaging. We also obtained the dependence of the maximum wetted area on the surface temperature.

EXPERIMENTAL METHOD

In order to measure the exact contact area between an impinging droplet and a surface during impact, we used the total internal reflection (TIR) method (Axelrod et al. (1984), Huang et al. (2006), Sadr et al. (2005) and Kolinski et al. (2012)). When an incident laser beam impinges an interface between two mediums with different indices of refraction (for instance, from air to glass), the beam will be either reflected back to the incident medium or refracted into the other medium depending on the incident angle and the indices of the two mediums. A larger incident angle measured from the normal direction to the interface results in a more diversion in the refracted beam. When this incident angle θ_i is equal or larger than a critical angle, defined as $\theta_c = \sin^{-1}(n_1/n_2)$, the beam will be totally reflected back into the incident medium. Here n_1 is the index of refraction of the less dense medium (air) and n_2 is that of the denser medium (glass). At the interface, there is a part of the incident energy that penetrates through the medium of lower index of refraction (air). This so-called evanescent wave propagates in the less dense medium parallel to the interface; its intensity decays exponentially with distance from the interface (Axelrod et al. (1984)):

$$I = I_0 \exp(-z/z_h), \quad (1)$$

where I_0 is the intensity of electric field at the interface ($z = 0$), z is the distance from the interface, and z_h is the penetration depth which depends on the incident angle, indices of refraction of two mediums and the wavelength of incident light in vacuum, λ_0 :

$$z_h = \frac{\lambda_0}{4\pi} (n_2^2 \sin^2 \theta_i - n_1^2)^{-1/2}. \quad (2)$$

In our experiment, we implement the TIR method as follows: We use an uncoated prism of N-BK7 glass with the index of refraction $n = 1.52$ and the corresponding critical angle $\theta_c \approx 42^\circ$. A green laser light (532 nm) is directed to the prism using a mirror. The laser beam then hits the upper surface of the prism at an angle slightly larger than θ_c at the glass-air interface to provide the necessary condition for TIR ($\theta_i > \theta_c$). It is then reflected from the upper surface and directed toward a high-speed camera (SA-X, Photron Inc.) by another mirror (see figure 1 for schematic). This camera captures the bottom view of the impacting droplets. The bottom-view recording is then used to extract the exact contact area between the liquid and the surface. We used another synchronous high-speed camera (APX, Photron Inc.) to capture the droplets from the side. From the side-view recordings, we obtain the velocity V and droplet diameter D_0 before impact, which respectively are $D_0 = 1.8 \text{ mm}$ and $V = 2 \text{ m.s}^{-1}$. We then calculate the Weber number $We = \rho V^2 D_0 / \sigma$, which compares the droplet kinetic energy with its surface energy. Here ρ is the density and σ is the surface tension of the liquid. The corresponding Weber number in this study is $We = 260$.

Figure 1. Schematic (not to scale) of the experimental setup to observe the impact from the bottom using a high-speed camera (SA-X) and from the side using a synchronous high-speed camera (APX).

The working liquid used in our experiment is ethanol with density $\rho = 789 \text{ kg.m}^{-3}$, surface tension $\sigma = 22.39 \text{ mN.m}^{-1}$, viscosity $\mu = 1.04 \text{ mPa.s}$, and the boiling point $T_c = 78.4^\circ\text{C}$. In order to vary the temperature of the prism, we placed it on an aluminum holder which can be heated up to 180°C using two cartridge heaters. The temperature of the aluminum holder is measured by a K-type temperature probe. It was assumed that the temperature measured by the probe and that of the prism are the same (we have verified that the temperature difference is at most 3K).

RESULTS AND DISCUSSIONS

In figure 2, several snapshots of an ethanol droplet impacting on a glass prism are shown for both side and bottom views at two different surface conditions: $T = T_{\text{room}} = 25^\circ\text{C}$ and $T = 180^\circ\text{C}$. It should be noted that the reference time, $t = 0$, is taken when the first contact between ethanol and the glass surface is observed by the bottom-view camera. When the liquid wets the surface, the total internal reflection condition for the glass-air interface does not hold for the glass-liquid interface, and the laser light thus exits to the liquid phase instead of being reflected back to the glass. Therefore, the dark and bright areas respectively correspond to the wetted and dry ones. Figure 2a shows several bottom- and side-view snapshots of an impacting droplet on a surface at room temperature. There is a distinct difference between the dry and wetted areas as they appear on the recorded images. Note that the grey regions with dark and bright fringes (as indicated by the arrow) are caused by the interference of the light reflected from the glass-liquid interface and that from the liquid's top surface, thus they are not representative of dry areas. Figure 2b shows the bottom- and side-view snapshots of an impacting droplet on a superheated surface at $T = 180^\circ\text{C}$. The formation and growth of vapor bubbles at the glass-liquid interface is clearly seen with the appearance of tiny bright spots ($t = 1.5\text{ms}$), which become larger with time ($t = 9.1\text{ms}$). The corresponding side-view snapshots show ejected droplets as a result of the venting of the vapor bubbles.

Figure 2. Bottom-view and side-view snapshots of the impact of droplets for surfaces at different temperatures. a) $T = 25^{\circ}\text{C}$ (room temperature): Upon impact, the droplet completely wets the surface. The arrow shows the fringes caused by the interference and is still indicative of wetted area; b) $T = 180^{\circ}\text{C}$: The spreading of the liquid is accompanied by the boiling process. The arrows in the bottom views indicate nucleation and growth of vapor bubbles at the glass-liquid interface. The arrows in the side views show the ejected droplets as a result of the expanding bubbles on the glass-liquid interface.

In figure 3, the wetted area obtained from bottom views is plotted as a function of time for different temperatures in the range of $25 - 180^{\circ}\text{C}$. For $t < 2\text{ms}$, all the curves almost overlap, indicating that the boiling process weakly affects the spreading at the very early stage of the impact. By increasing the temperature, the droplet spreads more on the surface and the wetted area is increased because the surface tension of ethanol decreases with temperature. We confirm that by plotting the maximum wetted area A_{max} as a function of surface temperature and show it in figure 4. As it can be seen, A_{max} first reduces to reach a minimum value at $T = 45^{\circ}\text{C}$ and then gradually increases with temperature up to 180°C . We also observe that at higher temperatures ($T \geq 160^{\circ}\text{C}$), the wetted area first increases to a maximum value and then decreases with a higher rate compared to that of impact on lower temperature surfaces. This is because of the fact that vigorous boiling that occurs at the higher surface temperatures quickly dries out the surface (see Figure 2b).

Figure 3. Variation of wetted area with time at different temperatures ($D_0 = 1.8$ mm, $V = 2$ m.s⁻¹, $We = 260$).

Figure 4. Maximum wetted area at different temperatures ($D_0 = 1.8$ mm, $V = 2$ m.s⁻¹, $We = 260$).

CONCLUSIONS

In this paper, the impact of ethanol droplets on solid glass surface of prism was studied experimentally using the method of total internal reflection (TIR). The experiments were done for the impact of droplets on substrate at different temperatures between 25 – 180°C. By using TIR, the exact areas of the wetted surface were obtained as functions of time and analyzed for different temperatures.

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