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Impact Dynamics of a Droplet on a Heated Surface

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Abstract - The effect of impact velocity and substrate temperature on the impact dynamics of a water droplet on a non-heated and heated glass substrate is studied. A high-speed camera is utilized to record the time-varying droplet shapes during the impact. The initial spreading of the droplet is driven by large kinetic energy with large deformation of the free surface. The droplet recoils due to conversion of the surface energy to the kinetic energy and the internal flow reverses to radially inward. The liquid-gas surface oscillates along with the flow reversal from axially upward to axially downward, due to competition between the surface and kinetic energy. The amplitude of oscillation damps due to viscous dissipation and droplet assumes a spherical cap shape after it comes to rest. A lager impact velocity corresponds to higher kinetic energy and oscillations take longer time to dissipate. As the temperature of the substrate increases, the droplet spreads lesser due to larger resistance to the wetting at the contact line.

Keywords**:** Droplet Impact Dynamics, High-Speed Visualization.

1. Introduction

There are several technical applications of droplet impact dynamics on solid surface. Examples include, inkjet printing, spray evaporative cooling, rapid prototyping etc. Droplet impact dynamics on heated surface is a highly transient process involving the spreading, recoiling, bouncing, droplet break-up, and splashing (see review by Yarin [1]).

In a notable paper, Chandra and Avedisian [2] visualized the impact of 1.5 mm diameter n-heptane droplet on a polish stainless steel surface using flash photography and studied the effect of substrate temperature on the impact dynamics. Rioboo et al. [3] recorded impact of different liquids on a solid surface with different wettabilites and showed different outcomes - splash, rebound, partial rebound, deposition. Dam and Clerc [4] investigated the impact dynamics of a water droplet on a glass substrate and recorded bubble entrapment in the droplet during the impact. Pasandideh-Fard et al. [5] experimentally investigate the impact of a water droplet on heated stainless steel surface and reported that the droplet cooling effectiveness increases with Weber number for fixed Reynolds number. Bhardwaj et al. [6] experimentally investigated the impact of heated droplet on a surface at ambient temperature and concluded that spreading of warm droplet is more compared to cold droplet because of larger Reynolds number. In follow-up paper [7], they recorded the impact of isopropanol droplet on a heated glass substrate and found a non-monotonic variation of the temperature at the impact point on the surface during the early stages of the impact. Khavari et al. [8] studied impact of a ethanol droplet on heated glass surface and recorded the following regimes: spreading, bubbly boiling and fingering boiling. Very recently, Mitrakusuma et al. [9] experimentally investigated the effect of surface wettability on the impact dynamics and showed larger wettability corresponds to larger spreading during the spreading on heated surface.

To this end, a combined effect of impact velocity and substrate temperature on the impact dynamics is poorly understood. The objective of the present paper is to systematically study the effect of impact velocity (or Weber number) and substrate temperature on the impact dynamics. We study water droplet on glass surface and the substrate temperature is kept below the boiling point of the liquid.

2. Experimental Setup

The schematic of the experimental setup used in the present study is shown in Figure 1(a). The main components of the setup are as follows: Droplet generation using a syringe, heating of the solid surface using a digital hot plate, high-speed camera. The droplet is deposited on the surface using a syringe attached to a retort stand, which can be adjusted to the distance between the substrate and the needle to obtain the required impact velocity. We used glass slide (Sigma-

Aldrich Inc.) as a substrate which were cleaned by isopropyl alcohol and deionized water and were allowed to dry in the ambient air. The glass surface is heated to different temperatures (50°C to 90°C) using a digital hot plate (Cole –Parmer Inc.). The droplet was deposited on the surface after the desired temperature is reached on the surface and remained steady for couple of minutes. The droplet impact on the solid surface was visualized from the side using a high-speed camera (MotionPro, Y-3 Classic) with long distance objective (Qioptiq Inc.) as shown in setup in Fig 1(a). A white LED lamp was used a backlight source for a high-speed camera. The images are recorded at 2500 frames per second. For the camera, the working distance, image resolution, and pixel resolution are 9.5 cm, 320 × 288 and 14 µm/pixel. The recorded image data were analyzed using MATLAB image processing module. All experiments were performed in a controlled environment at 27±1.5°C ambient temperature and 35±4% relative humidity.

3. Results and Discussion

We present results of the impact dynamics of a water droplet on a glass surface. The range of impact velocity and substrate temperature are U_0 = [0.396, 0.805] m/s and T_s = [28 - 90]°C, respectively. We keep the substrate temperature below the boiling point of the water. The corresponding range of Reynolds number ($Re = \rho U_0 D_0/\mu$) and Weber number ($We = \rho U_0^2 D_0/\gamma$) are Re =[777, 1655] and We = [3.7, 16.28], respectively, where ρ, U_0, D_0, μ, and γ are density, impact velocity, initial droplet diameter, dynamic viscosity, and surface tension, respectively.

Figure 1(b) shows the time-varying droplet shapes recorded from side by high-speed visualization for the impact of 1.7 mm water droplet on a glass substrate for different cases of T_s = 28°C, 60°C, and 90°C. U_0 in all cases is 0.396 m/s. As the droplet touches the surface, it spreads immediately. The initial spreading is driven by the large kinetic energy with large deformation on the liquid-gas free surface. At the instance of maximum spreading (t ~ 4.39 ms, T_s = 28°C), the droplet height reaches its minimum value and the maximum width $d_{\max}$. For T_s = 60°C and 90°C, we found instant of maximum spreading is 3.95 and 4.39 ms, respectively. At this instant, the kinetic energy of droplet almost becomes negligible and surface energy reaches to maximum value [10]. At t = 5 ms, the droplet recoils due to the conversion of surface energy to the kinetic energy, and the internal flow changes to radially inward. Figure 1(c) compares the droplet spreading behavior for three different temperatures at U_0 = 0.396 m/s (Re = 777, We = 3.7). In the figure, the time-varying droplet wetted diameter and height is plotted. At T_s = 28°C, the spreading of droplet is larger as compared to that of the results at T_s = 60°C, and 90°C. As pointed out by Chen et al. [11], during the spreading of the droplet, the evaporation near the contact line is larger than that on lower temperature substrate and consequently higher substrate temperature aids the resistance to the droplet spreading. Thus, as the substrate temperature increases, we observe lesser wetted diameter and a slight increase in the contact angle. In Figure 1(c), an equilibrium contact angle on glass at T_s = 28°C, 60°C and 90°C is 43.78°, 44.29° and 45.17° respectively. Similar kind of observations were reported by Bhardwaj et al. [7]. Moreover, the amplitude of oscillations in the droplet the height is found to increase with increase in the substrate temperature in Figure 1(c). Due to increase in substrate temperature, the droplet viscosity and surface tension decreases and the values of Re and We increase. Thus, the kinetic energy comparatively increases and requires more time to dissipate. In general, the viscosity of the liquid damps the oscillations. Therefore, at T_s = 28°C, droplet comes to rest earlier (around 50 ms), and at T_s = 60°C and 90°C, the time to completely damp out the oscillations are 60 ms and 70 ms, respectively.

Figure 1(d) shows the impact dynamics at U_0 = 0.805 m/s [Re = 1655, We = 16.28]. Similar results are observed as seen in Figure 1(c). The lesser spreading is observed for higher substrate temperatures. In Figure 1(d), an equilibrium contact angle on glass at T_s = 28°C, 60°C and 90°C is 41.38°, 50.38° and 57.66° respectively. Here, because of larger Re and We, the droplet wetted diameter spreads 36% more at temperature 28°C and 24% more each at temperature 60°C and 90°C respectively in comparison to that for U_0 = 0.396 m/s. While the droplet height is 25%, 29%, and 29% lesser for 28°C, 60°C, and 90°C, respectively. A larger Re corresponds to a more kinetic energy which ultimately results into more spreading and the amplitude of oscillation of the droplet larger compared to lesser impact velocity. The time required to completely damp out the oscillation is around 130 ms, 160 ms and 180 ms for 28°C, 60°C, and 90°C, respectively.

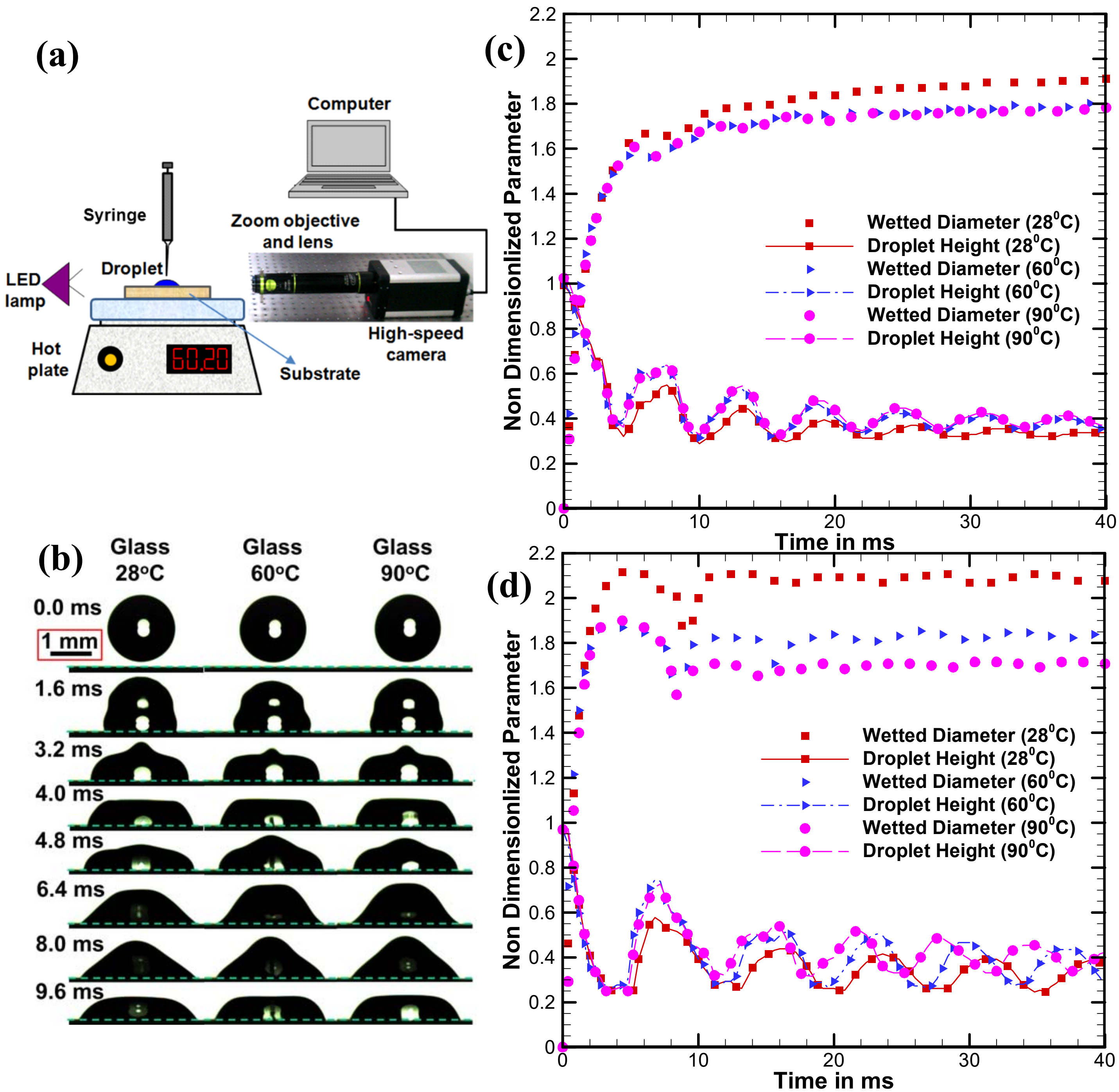

Fig. 1: **(a)** Schematic representation of experimental setup **(b)** High-speed side visualization of the impact of microliter water droplet of 1.7 mm diameter on a glass substrate at different temperatures. Impact velocity is 0.396 m/s. The scale is shown in the image at the top left. **(c,d)** Comparison of temporal variation of wetted diameter and droplet height during the impact of 1.7 mm water droplet on glass substrate kept at three different temperatures. Droplet falls on the substrate with impact velocity of **(c)** $v_0 = 0.396$ ms^{-1} ($Re = 777$, $We = 3.76$), and **(d)** $v_0 = 0.805$ ms^{-1} ($Re = 1655$, $We = 16.28$).

4. Conclusions

The impact of a water droplet on a glass for three substrate temperatures and two droplet impact velocity is presented. The results show mainly two outcomes: First, the droplet spreading decreases with increase in substrate temperature. The heating of the substrate aids to the resistance of wetting due to larger evporation at the contact line in the spreading process. Second, the amplitude of oscillations of the droplet free interface (or droplet height) increases with increase in substrate temperature and the time taken to droplet comes to the rest increases as viscosity of droplet decreases due to increase in substrate temperature. The present results are helpful to design applications such as spray evaporative cooling.

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