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CONTACT ANGLE DYANMICS OF DROPLETS IMPACTING ON FLAT SUBSTRATES

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Summary An experimental study is presented on contact angle dynamics of water droplets impacting on smooth surfaces with widely disparate wetting characteristics (wetting to non-wetting). Fundamental information relating to the relation between apparent (macroscopic) contact angle θ and contact line speed V_{CL} is presented. The impact conditions correspond to $Re = O(100) - O(1000)$, $We = O(1) - O(10)$, $Ca = O(0.001) - O(0.01)$, $Oh = O(0.001)$ and $Bo = O(0.1)$. For wetting configurations, the classical θ vs. V_{CL} trend is observed, while for partially wetting configurations, advancing contact angles are found to be insensitive to contact line speed. Impact on non-wetting surfaces is followed by rebound, and reveals that both advancing and receding contact angles do not change with contact line speed. The combined molecular-hydrodynamic theory predicted θ -V_{CL} trend data satisfactorily yielding physically reasonable molecular constants.

INTRODUCTION

Droplet impingement phenomena [1] are relevant to a host of emerging technologies. In free form manufacturing [2] for example, droplets of materials can be repeatedly dispensed in their molten form and subsequently solidify upon impact, producing a desired shape or structure. Sophisticated numerical models have been developed to investigate the cumulative effect of the multitude of droplet impingement parameters [3]. The evolution of the contact angle during droplet spreading contains largely unresolved physics. Intermolecular forces govern the microscopic dynamics of contact angle at the molecular level [4]. Furthermore, comparison of hydrodynamic theories and experiment for systems where the liquid does not completely wet the target surface gives physically unreasonable parameters such as subatomic slip lengths (λ). The θ -V_{CL} trend is not well established in forced droplet spreading. There exists a few studies on the combination of hydrodynamic and molecular theories and these models proved satisfactory in predicting θ vs. V_{CL} data in some forced spreading systems [6]. In view of the need for data on contact angle variation with contact line speed for various surfaces, no dynamic contact angle data has been reported to date for impact on super-hydrophobic surfaces. Recent droplet impact studies on such surfaces have considered the effect of impact inertia and droplet size on the residence time of droplets on the substrates. The aim of the present study to experimentally investigate dependence of contact angle θ on contact line speed V_{CL} for impact spreading droplets on surfaces with different degrees of wetting and to test the applicability of the combined molecular-hydrodynamic model.

EXPERIMENTAL

Using an infusion pump, single, distilled water drops of controlled size ($D_0=1.38 \pm 0.03$ *mm*) and velocity ($V_0 = 0.45$ *and* 0.77 *m/s*) were injected onto three different horizontal dry surfaces corresponding to wetting, partially wetting and non-wetting configurations. High-speed digital motion pictures of single droplet impact and spreading were recorded at 3000-5000 frames/s with a 1280×168 pixel resolution using a *Redlake* Motion Pro image analyzer at 54 µs exposure rate. Measurements of droplet spread diameter and contact angle were made by a commercial image processing software. The resolution of the droplet diameter measurements was ± 0.02 *mm*. Macroscopic (apparent) contact angle measurements were made from the captured images with a resolution estimated to be $\pm 5^o$.

RESULTS AND DISCUSSION

Figure 1a represents a typical droplet impact sequence recorded during an experiment. The backlit droplets appear dark against a bright background. The "mirroring" of the droplet on the polished substrate below can be seen in all images. The severe free surface deformation seen in the early impact stages in Fig. 1 is accompanied by the formation of horizontal ripples on the liquid/gas interface. Gradual flattening of the droplet occurs next, with subsequent recoil and eventually droplet rebound at 8.4 ms on the non-wetting surface. It is emphasized that rebound did not occur during impact on any of the wetting and partially wetting substrates. As can be seen, apart from the early impact dynamics, droplet spreading and contact angle dynamics are totally different on the three surfaces studied. It was observed that due to high inertial energy of the impacting droplet, forced spreading dynamics with □ $>90^o$ is independent of surface-fluid wetting interactions. In all spreading curves, dimensionless contact diameter increased with approximately $t^{0.5}$ until it reached to the maximum value. It was also found that under the given impact conditions, as the degree of target surface wetting decreases droplet diameter at maximum spreading (D_{max}/D_o) decreases. The capillarity force arising from the difference between equilibrium droplet shape and extensively deformed droplet shape drives recoiling flow. In our study, the primary spreading of water droplets belongs to the inviscid, impact-driven flow regime since $We>1$ and $Oh<We^{1/2}$. However, during final stages of spreading contact line motion slows down and viscous effects become significant. Therefore, droplet dynamics is governed by the capillary-driven regime. In this regime, it is *Oh* that

determines whether the resistance to flow is dominantly viscosity (high *Oh*) or inertia (low *Oh*). For the impact conditions studied herein, $Oh=0.0032$ ($We<50$), both the inertia and the viscous forces play significant roles in resisting the flow. Thus, recoiling is vigorous. In the non-wetting case, the recoiling rate is very similar to the spreading rate, thus indicating minimal interaction between the liquid and the substrate. Four different graphs given in Figure 1b detail the dependence of the contact line speed on the dynamic contact angle on all surfaces. Since on the partially wetting surface droplet recoils more than once, its first and second cycles were separately plotted. For the case of *wetting* and high impact inertia (V_0 = 0.77 m/s) the advancing contact angle increases with contact line speed. Although the trend is similar to that of spontaneous spreading, the data could not be fitted with the classical parameters of the Hoffman hydrodynamic theory. The analytical study of Hoffman suggested that flow inertia could influence contact line velocity dependence of dynamic contact angle for We > 0.015 [5]. The analyses of hydrodynamic theories focused on the slow viscous flow regime, neglecting flow inertia in the Navier-Stokes equations. As will be shown, however, the combined molecular-hydrodynamic theory predicts θ vs. V_{CL} trend on wetting and partially wetting surfaces.

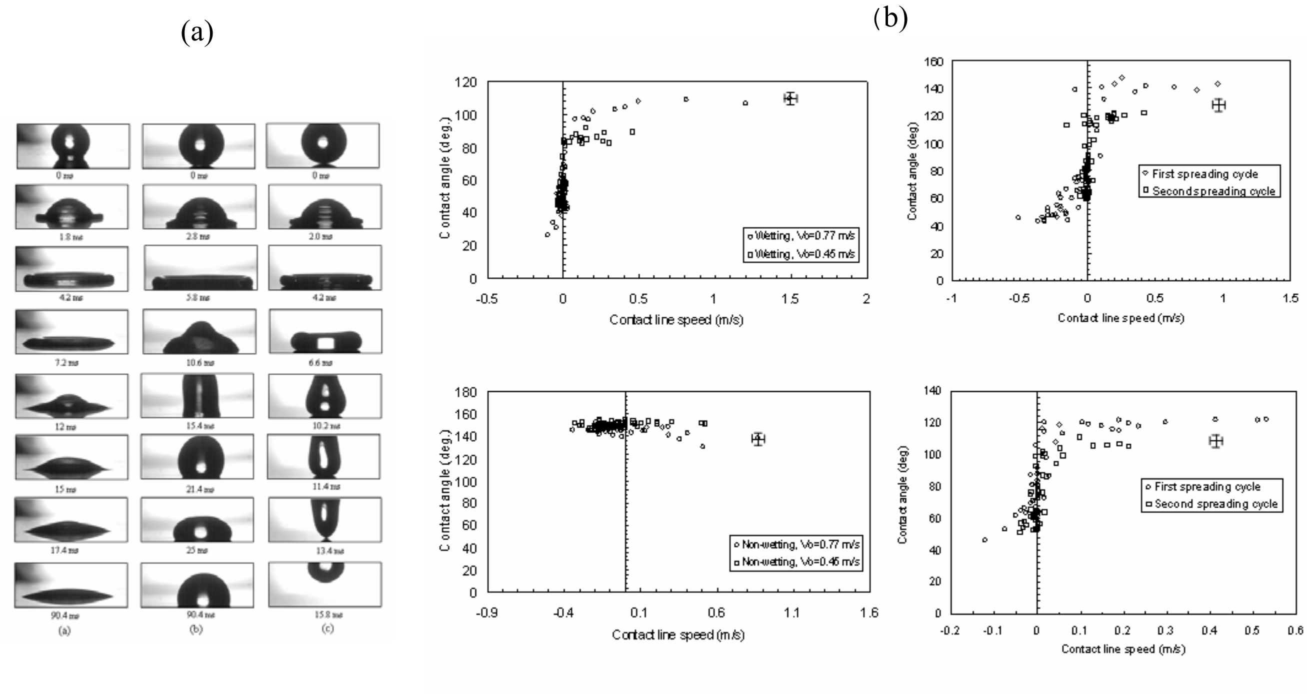

Figure 1. Sequence of time evolution of droplet impact on three different surfaces (a) and contact line speed dependence of the contact angle for all the surfaces studied (b).

CONCLUSIONS

By correlating the temporal behaviors of apparent contact angle θ and contact-line location, the angle vs. speed relationship was established. For wetting configurations, the classical θ vs. V_{CL} trend was observed both for advancing and receding conditions. For partially wetting configurations, advancing contact angles were found to be insensitive to contact line speed, while receding contact angles followed the classical trend. Impact on non-wetting surfaces was followed by rebound, and showed that both advancing and receding contact angle values did not change much with contact line speed. It will be shown that the combined molecular-hydrodynamic theory can be used in the modeling of θ -V_{CL} trend on wetting and partially wetting surfaces.

References

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