Temperature dependent droplet impact dynamics on flat and textured surfaces

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Droplet impact dynamics determines the performance of surfaces used in many applications such as anti-icing, condensation, boiling, and heat transfer. We study impact dynamics of water droplets on surfaces with chemistry/texture ranging from hydrophilic to superhydrophobic and across a temperature range spanning below freezing to near boiling conditions. Droplet retraction shows very strong temperature dependence especially on hydrophilic surfaces; it is seen that lower substrate temperatures lead to lesser retraction. Physics-based analyses show that the increased viscosity associated with lower temperatures combined with an increased work of adhesion can explain the decreased retraction. The present findings serve as a starting point to guide further studies of dynamic fluid-surface interaction at various temperatures. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.3692598]

Many surface engineering applications involve impinge-ment of water droplets; the performance of the surface depends significantly on the nature of fluid-surface interaction. Furthermore, droplet impingement can occur in a very wide temperature range. An illustration in the low temperature regime is the use of superhydrophobic surfaces for anti-icing applications, where the study of droplet impact dynamics is vital to estimate the interfacial contact area which provides nucleation sites for icing. At the other end of temperature spectrum, a study of impact dynamics on various surfaces has applications in the areas of spray cooling and boiling heat transfer.9,10 The phenomenon of condensation in heat exchangers also involves the dynamic interaction of liquid droplets on surfaces. Understanding the influence of temperature on the fluid-surface interactions is therefore vital for controlling phase change phenomena.

Droplet impact dynamics has previously been studied for different surface-liquid-temperature combinations; however most of the studies are confined to narrow parameter ranges. Furthermore, in the field of superhydrophobicity, most existing studies have considered static droplet-fluid interactions only.12–15 Impact dynamics on superhydrophobic surfaces has been studied16–19 for multiple surface architectures (morphology and chemistry) under various impact conditions (droplet size and velocity) using both experimental and theoretical approaches; however most of these studies were at room temperature conditions. There are very few studies1,2,20–22 on temperature dependent droplet impact dynamics on various surfaces.

An analysis of the literature thus indicates that there is no available comprehensive study that analyzes the influence of temperature, surface chemistry, and texture over a wide parameter space. In this paper, the temperature dependency of impact dynamics on various surfaces is studied. Experimental results and analyses are presented to quantify the influence of the above parameters on the interfacial contact area at all stages during droplet spreading and retraction. The interfacial contact area is the critical parameter which determines the system performance; as an illustration, it determines the onset of freezing in icing environments and heat transfer rates in condensation applications.

Droplet impact dynamics on six surfaces (with wettability ranging from hydrophilic to superhydrophobic) were studied (Table I) in the temperature range of −15 to 85 °C. These surfaces were selected to enable a study of the influence of surface chemistry as well as texture on impact dynamics (see supplementary material).

Room temperature deionized water droplets (diameter 2 mm) were impacted on these surfaces, with the surface temperature varying between −15 °C and 85 °C. The tests were done at an impact velocity of 2.2 m/s, which corresponds to a Reynolds number \( Re = \frac{Vd}{\nu} = 4400 \) and a Weber number \( We = \frac{\rho V^2 d}{\sigma} = 138 \) at room temperature (\( d \) is the initial droplet diameter, \( \rho \) is the density, \( V \) is the impact velocity, and \( \gamma \) is the surface tension of water). At higher Weber numbers, the droplet can rupture upon impact or pin on textured surfaces due to the Cassie-Wenzel transition.23 All experiments were conducted in a nitrogen environment resulting in a relative humidity of less than 2%. The wetting dynamics was captured using high speed imaging of the impingement.

TABLE I. Morphological and static wettability characteristics of representative surfaces.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Morphology</th>
<th>Static contact angle</th>
<th>Roll off angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>Flat</td>
<td>15°</td>
<td>No roll off</td>
</tr>
<tr>
<td>Si-PEG</td>
<td>Flat</td>
<td>44°</td>
<td>No roll off</td>
</tr>
<tr>
<td>Si-Trifluoro</td>
<td>Flat</td>
<td>80°</td>
<td>No roll off</td>
</tr>
<tr>
<td>Si-F</td>
<td>Flat</td>
<td>104°</td>
<td>No roll off</td>
</tr>
<tr>
<td>Si-Stex-F</td>
<td>Single textured</td>
<td>145°</td>
<td>37°</td>
</tr>
<tr>
<td>Si-DTex-F</td>
<td>Double textured</td>
<td>149°</td>
<td>11°</td>
</tr>
</tbody>
</table>

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spreading, retraction, and stabilization phase of droplet impact. A high-speed Phantom V7.3 camera (from Vision Research) with video recording capabilities at 3000 frames per second was used.

One of the focal points of this work is to understand the intricacies of droplet impact dynamics on a variety of surfaces and to differentiate between static and dynamic wettability in terms of the final droplet-surface contact area. Representative high-speed images of room temperature water droplet impact on Si-PEG (hydrophilic) and Si-DTex-F (superhydrophobic) substrates at room temperature are shown in Figure 1(a). After reaching the maximum spread diameter, the droplets recoil and oscillate before reaching a final state. Wetting dynamics is quantified by measuring the droplet radius from the high speed video images (Figure 1(b)). Figure 1(b) shows the transient variation of the spread diameter, at room temperature, on five substrates. Very limited recoil is observed for the Si and Si-PEG surfaces, whereas significantly larger recoils are seen on Si-Trifluoro and Si-F surfaces. The droplets, however, remain completely pinned to these surfaces during retraction. In contrast, droplets bounce off the superhydrophobic Si-STex-F and Si-DTex-F substrates. Each droplet may experience several bounces on a superhydrophobic surface before coming to rest. It should be noted that while the impact dynamics on the two textured surfaces is rather similar under current experimental conditions, the double textured morphology is more desirable due to its higher resistance to wetting pressures. The maximum spread and the final state spread diameters are a function of the initial droplet size, droplet velocity, and water-surface tension. However, the final state diameter is a much stronger function of the surface hydrophobicity (see supplementary material). The water-substrate contact area, subsequent to impact, recoil, and equilibration, can be estimated from the final state diameter. Figure 1(c) highlights the difference between the droplet-surface contact area under dynamic and static conditions. It is seen that the final contact area after droplet impact can be drastically different from the contact area of a static (or gently positioned) droplet on that surface, especially for hydrophilic surfaces. The trend in Figure 1(c) may not reflect the behavior of superhydrophilic substrates with very low contact angles (<10°). In this case, the static contact area would be very small, thus the ratio of dynamic to static contact area should approach 1. These observations underscore the limited utility of static wettability measurements in understanding dynamic wettabilities, which as mentioned earlier are prevalent in many practical applications.

The influence of surface temperature on impact dynamics was investigated by varying the substrate temperature between −15°C and 85°C while maintaining the initial droplet temperature at 22°C. Figures 2(a)–2(c) show the transient spread diameter curves at three surface temperatures for the hydrophilic (Si-PEG), hydrophobic (Si-F) and superhydrophobic (Si-DTex-F) substrates, respectively. The effect of substrate temperature is very pronounced for the hydrophilic substrate, where a significant slowing down of...
the retraction process is observed at lower temperatures. Substrate temperature has a similar but weaker effect on the hydrophobic Si-F substrate. However, the effect of temperature is completely negligible for the single and double textured superhydrophobic samples, as shown in Figure 2(c). It should be noted that the low temperature experiments are not impacted by ice nucleation at below freezing temperatures. This was verified by conducting control experiments, wherein salt water droplets were impinged on these surfaces instead of pure de-ionized (DI) water. Addition of the salt reduces the freezing point to ~30 °C. Very similar results were obtained on both pure DI and salt water droplets indicating that ice nucleation is not a significant consideration in the timescales of droplet spreading and retraction.  

A simple physics-based model can explain the above observations. The initial energy of the droplet before impact consists of the kinetic and surface energy components. During the spreading and retraction phases, viscous dissipation and contact line friction cause energy dissipation; in this study, it is assumed that the contact line friction (which causes hysteresis) also leads to energy dissipation; in this study, it is assumed that the contact line friction does not change with substrate temperature. 

As shown in Figure 2, the effect of surface temperature on droplet impact dynamics is not uniform across the different samples. The strong coupling between the surface temperature and surface chemistry is clearly shown when examining the droplet retention factor on the surface, which is defined as $\frac{\text{Area}_{\text{final}}}{\text{Area}_{\text{contact}}}$. The maximum and final contact areas are estimated from the droplet maximum spread and final state spread diameters. Figure 3 shows the variation of the retention factor as a function of $(1 + \cos \theta) \times \text{normalized viscous loss}$. For each surface, the viscous dissipation losses are normalized with respect to the corresponding viscous dissipation value for impact at 22 °C. The experimentally determined retention factors fall on the same line which passes through the origin. In other words, the retraction factor can be written as

$$\text{Retention factor} = \frac{\text{Area}_{\text{final}}}{\text{Area}_{\text{contact}}} \times \frac{\text{Viscous loss}(T)}{\text{Viscous loss}(T_0)}$$  \hspace{1cm} (2)

The first term in Eq. (2) is related to energy losses due to adhesion (the work of adhesion is $W_a = \gamma(1 + \cos \theta)$), while the second term represents the energy losses associated with viscous dissipation, as described earlier. Accordingly, high viscous dissipation losses (lower temperatures) combined with strong water-surface interactions (large adhesion) lead to very low mobility of water during recoil, where a retention
factor of almost 1 is observed for highly hydrophilic surfaces. In contrast, complete retraction of water is observed on superhydrophobic surfaces, which are represented with the blue symbol at the origin in Figure 3. This observation, which implies low viscous dissipation and low adhesion losses, is in full agreement with previously observed low drag properties of superhydrophobic surfaces. The temperature invariant nature of droplet impact on textured superhydrophobic surfaces can be explained by heat transfer considerations. The magnitude of heat transfer from a superhydrophobic surface to a droplet is significantly reduced due to the presence of a thermal resistance (air gap) beneath the hydrophobic surface to a droplet is significantly reduced due to the presence of a thermal resistance (air gap) beneath the hydrophobic surface.  

The strong temperature dependence on hydrophilic surfaces indicates that more analysis is needed before using such surfaces in applications such as wicking or oil-water separation. Similarly, the role of viscous dissipation and friction is particularly important at subzero temperatures and should be investigated in more detail. In contrast, textured superhydrophobic surfaces show temperature invariant impact dynamics; this significantly increases their desirability for applications in both low and high temperature regimes.

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32See supplementary material at http://dx.doi.org/10.1063/1.3692598 for further details of the fabrication and measurement of static wettability on these surfaces.