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Dynamic water contact angle during initial phases of droplet impingement

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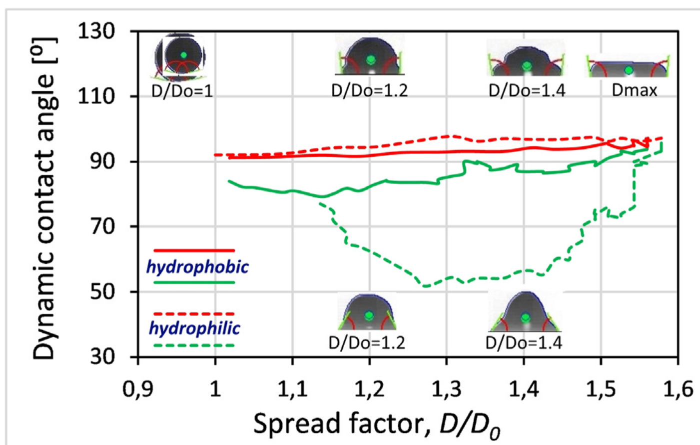
HIGHLIGHTS

- Contact angle dynamics in the initial stages of droplet impact at low Weber numbers.
- The dynamic CAs significantly differ from the static and quasi-static CAs.
- The spreading (advancing) phase dominated by inertia forces.
- The CAs in the receding phase sensitive to surface wettability.
- No simple relationship between the classic CA hysteresis and the dynamic counterpart.

GRAPHICAL ABSTRACT



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ABSTRACT

We investigate the dynamics of water contact angle during droplet impact onto substrates with three different surface coatings (one hydrophilic and two hydrophobic). The experiments are carried out for three Weber numbers (*We*) of approximately 5, 7 and 10. The dynamic contact angle is determined by analysis of consecutive frames of video recordings taken at a frame rate of 50 000 fps. Measurements are carried out for the first advancing (spreading) and receding (retracting) phases of droplet impingement. We find that the evolution of contact angle during impingement is not directly related to contact angle values obtained from traditional static and quasi-static measurements (sessile drop, tilting plate, or Wilhelmy plate methods). We propose that the dynamics of contact angle resulting from fluid flow more accurately reflects surface physico-chemical properties than the values obtained from static and quasi-static measurements.

1. Introduction

Collision of water droplets with a solid surface is a common phenomenon found in nature, technological processes and

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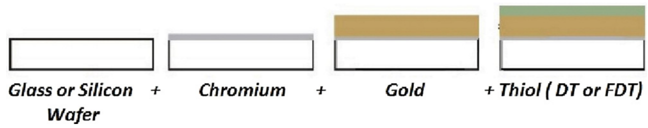

Fig. 1. Scheme of substrate coverage.

everyday life. The phenomenon was studied as early as in 1876 (see Worthington [1]) and intensively investigated during all of the 20th century, with a focus on wettability (Cassie [2]) or impingement ([3–8]). Recently, impact phenomena have also been studied for surfaces with special superhydrophobic properties, obtained by new chemical coatings (see Varanasi [9]), manufactured micro/nanostructure (see Bartolo [10]), or both (see, *e.g.*, Zhang [11], Michel [12], Boinovich [13,14]). Nevertheless, many questions regarding such interactions remain open or have been insufficiently explained. On the basis of the earlier research, one can distinguish several fundamental scenarios for droplet impinging onto different surfaces, such as spreading, spreading with bouncing, partial bouncing, jetting, *etc*. These scenarios are described in more detail by Liu [15], Rein et al. [16], Yarin [17], de Gennes [18] and Bobiński [19]. In general, the scenarios depend on surface and liquid properties, as well as on impact energy.

The partial and full rebound are of particular interest as mechanisms which can possibly facilitate the design of self-cleaning or anti-icing surfaces (see Zhao [20], Cao [21] and Remer [22]). The occurrence of the required impingement scenario (see [11,23]) has been usually correlated with the values of the static (wetting) contact angle, Θ_w and its hysteresis, $H_{\Theta,}$ determined using several established techniques. In particular, it has been conjectured that bouncing is more likely to occur on surfaces exhibiting high static values of Θ_w. It should be noted here that most practical measurements of Θ_w do not conform to the definition of the equilibrium wetting angle (the Young contact angle), which corresponds to ideal conditions at the phase boundary. On real solid surfaces, the Young contact angle is difficult, if at all possible, to measure and apparent contact angle is the measureable quantity [24,25].

The impingement process, on the other hand, is a highly dynamic phenomenon and measurements of the contact angle in static and quasi-stationary conditions (sessile drop, tilting plate, or Wilhelmy plate) may not be fully relevant to what happens during droplet collision. Some authors [24,26] use the notion of "dynamic contact" for a moving substrate (*e.g.*, a wall channel) and others, like Tretinnikov [27] or Dettre [28], apply it for the moving Wilhelmy plate. We follow here the terminology postulated by Marmur [25], who differentiates between quasi-static conditions and dynamic wetting conditions. In quasi-static conditions the triple phase line displacement occurs at low velocity (such conditions occur during contact angle hysteresis measurements, performed by increasing and decreasing the volume of sessile droplet or by tilting the substrate, and are also typical for the Wilhelmy plate technique) [29,30]. Dynamic conditions stand for the triple line moving at high velocity, which is typical for droplet impingement. Between these

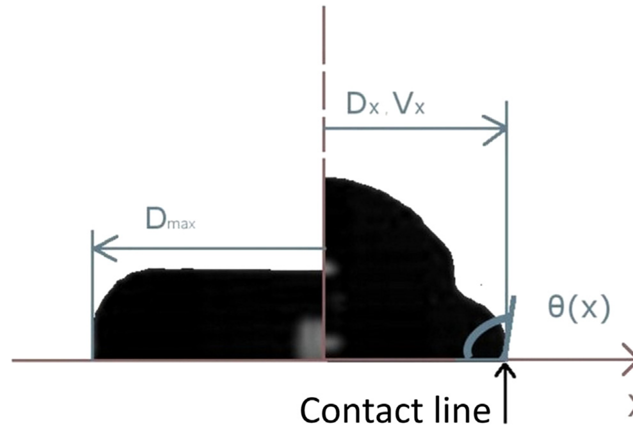

Fig. 3. Droplet dynamic parameters (photo taken at droplet impingement).

cases the Reynolds numbers, *Re*, differ by at least three orders of magnitude and therefore different physical phenomena may dominate.

Here, we investigate the dynamic (apparent) contact angle, which can be measured during real droplet collisions with solid surface, in the first few milliseconds of impingement. We assess the systematic differences, when compared with traditional static and quasi-static measurements. Precise information about the value of the contact angle formed in dynamic conditions is crucial for macro-scale numerical modelling of droplet impingement (*e.g.*, via the standard Navier-Stokes simulations). Such information is even more important for verification and calibration of mesoscale and microscale simulations (*e.g.*, via Lattice-Boltzman methods), which in principle allow to account for more complex surface properties [31].

To reduce the number of parameters that may influence the impingement scenarios, this investigation is focused on smooth, chemically functionalised surfaces and small *We*. Such a regime of *We* allows to avoid instabilities on the rim of the droplet [3].

Similar measurements of contact angles have been conducted before, *e.g.*, by Kannan et al. [32], but for a different range of parameters, or by Rioboo et al. [33], who considered the later stages of impingement only, when the diameter of the contact area remains constant. Bayer & Megaridis [34] discussed the evolution of the contact angle at the even later stages of impact.

The main parameters considered in the present investigation are described in Table 1.

We consider water droplet impingement on surfaces with different wettabilities. Microscopically smooth surfaces of sputtered gold and self-assembled monolayers (SAMs) of alkanethiolates on gold were used to provide a range of water static contact angles (WCAs) and contact-angle hystereses. Such surfaces were selected to minimise the possible influence of topography on wetting properties.

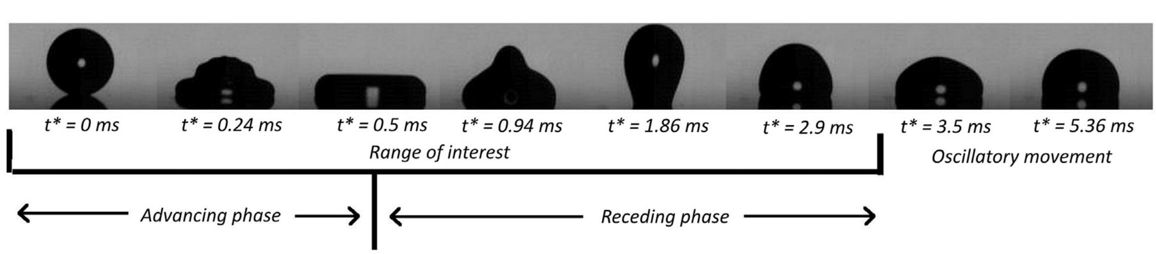

Fig. 2. Droplet impingement on hydrophobic surface with the time scale of interest indicated.