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Research Paper

Modelling droplet sliding angle on hydrophobic wire screens

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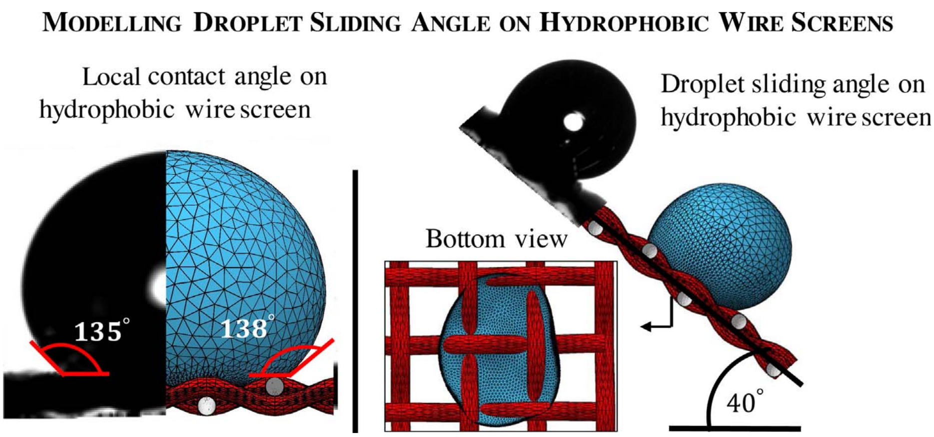
GRAPHICAL ABSTRACT



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ABSTRACT

This work presents a detailed investigation of the droplet lower and upper contact angles on hydrophobic wire screens with different properties such as wire diameter, wire spacing, or Young–Laplace contact angle. Numerical simulation and experiment were considered to better our understanding of the factors impacting droplet sliding on a hydrophobic screen, and to quantify their importance. To conduct the numerical simulations, the screens' geometry was programed in the Surface Evolver code, and the droplet shape was obtained by minimizing the total energy of the droplet–screen system iteratively using the code's finite element solver. Good general agreement was observed between the results of our numerical simulations and experimental data. Most interestingly, it was observed that droplet sliding angle increases with increasing the wire spacing in screens with a given wire diameter. To explain this counterintuitive observation, detailed quantitative information is presented in terms of the three-phase contact line on the droplet's receding side as well as the penetration of the air–water interface into the void space between the wires. The results of our study are discussed in the context of the contemporary literature.

1. Introduction

Wire screens treated with a hydrophobic coating have become a cost-effective way of creating a porous water repellent (or oil repellent if treated with an oleophobic coating) surface. Such porous structures have been considered for a variety of potential applications such as drag reduction on submerged surfaces [1–5], oil–water separation [6–11], heat transfer or anti-icing [12–14], self-cleaning [15–17], and fog

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Nomenclature

A	Area
A_w	Wetted area
A_{AW}	Air–water interface area
A_{SW}	Solid–water interface area
D^*	Dimensionless ratio
d_w	Wire diameter
E	Energy
F_G	Gravitational force
F_A	Adhesion force
f	Fraction of projected area of solid surface in contact with water
g	Acceleration due to gravity
h	Distance between droplet center and top surface of wire screens
m	Droplet mass
r_d	Droplet radius
r_f	Roughness of the solid surface in contact with water
s_w	Spacing between two consecutive wires
V	Droplet volume
w_d	Droplet width
θ_{adv}	Advancing CA
θ_{rec}	Receding CA
θ_l	Lower CA
θ_u	Upper CA
θ_A	Local CA
θ_{YL}	Young–Laplace CA
γ_{WA}	Surface tension
α	Sliding angle
δ	Immersion angle

Abbreviations

AWI	Air–Water interface
CL	Contact line
CA	Contact angle
CAH	Contact angle hysteresis
SE	Surface evolver
WA	Wetted area

harvesting [18–20] to name a few. The main attribute of a hydrophobic surface is the ability to reduce the area of contact between the solid surface and a body of water (often referred to as surface wetted area). While a reduced wetted area (WA) is the primary cause for achieving drag reduction in the case of a submerged hydrophobic surface [21–24], the problem becomes unfortunately more complicated when it comes to droplet mobility on the surface (e.g., in separating dispersed water droplets from diesel or oil droplets from engine exhaust). The complexity in predicting the degree of droplet mobility over a hydrophobic surface arises mainly from the fact that it depends on the WA of the solid surface, the length of the three-phase air–water–solid contact line (CL), the 3-D shape and orientation of WA and CL with respect to the direction of the droplet's motion, and the slope of the air–water interface (AWI) along the CL. Obviously, these factors depend strongly on both the surface morphology and on the physical properties of the droplet. An additional factor further complicating this problem is the tendency of the droplet to pin itself to certain local sites on the surface (caused perhaps by chemical or morphological non-homogeneities). These factors make it almost impossible to accurately predict the degree of droplet mobility over a hydrophobic surface via a first-principles theoretical approach. In the absence of a better option, droplet mobility over a hydrophobic surface has often been characterized empirically in terms of the droplet's advancing and receding contact angles (CAs) which are the CAs in the direction of droplet motion (most probably the largest and smallest CAs along the perimeter of the droplet) on that specific surface. One should keep in mind that there is nothing fundamentally important about the advancing and receding CAs other than they are easy to measure via imaging. In fact, the advancing and receding CAs are only two "dependent variables" that owe their values to a series of morphological (surface) and thermodynamic (droplet) "independent variables", and therefore their applicability is limited to the specific surface and droplet size used in measuring them. Because of these inherent limitations, the force required to detach a droplet from a surface is often presented in terms of the difference between the advancing and receding CAs (i.e., CA hysteresis) but multiplied by an empirical factor to compensate for the lack of sufficient information about the impact of the actual "independent variables" in this problem [25–34].

In the absence of pinning effects (e.g., the case of a surface with round asperities like those of a wire screen), a theoretical approach can be considered to predict the force of detachment (and of course the advancing and receding CAs) as was discussed in our previous work for droplet detachment from a single fiber [35,36]. In the current paper, we study the effects a screen's geometrical parameters on the mobility of droplets of different sizes on its surface via numerical simulation, for the first time. Complimentary experiments have also been conducted for model validation whenever possible. Furthermore, the main objective of the current work is to quantify the mobility of a droplet deposited on a hydrophobic wire screen, as it relates applications such as fog harvesting or droplet filtration/separation media.

Remainder of this paper is organized as follows. We first present a condensed review of the common knowledge regarding droplet CAs on flat and tilted surfaces in Sec. 2. We then discuss our numerical approach for modelling droplet over hydrophobic wire screens in Sec. 3 and our experimental approach in Sec. 4. Our results and discussion are given Sec. 5, followed by our conclusions in Sec. 6.

2. Advancing and receding contact angles on hydrophobic wire screens

On a rough surface the droplet exhibits multiple equilibrium states and apparent CAs. The apparent CA θ_{app} (averaged CA along the contact line) for a droplet, corresponding to the minimum global energy of the system, on an isotropic hydrophobic surface is given by [37–39].

$$cos\theta_{app} = r_f f cos\theta_{YL} + f - 1 \quad (1)$$

In this equation r_f is the ratio of the WA to its projected area on a horizontal plane, and f is the ratio of the same projected WA to the total projected contact area of the droplet with the surface. θ_{YL} is the Young–Laplace contact angle (YLCA) of a chemically identical smooth surface (see Fig. 1b). Treating the wire texture of a monofilament textile as an array of parallel cylinders, Eq. (1) was modified in [16] to predict the apparent CA of droplets on woven fabrics, i.e.,

$$cos\theta_{app} = \frac{1}{D^*}(\pi - \theta_{YL})cos\theta_{YL} + \frac{1}{D^*}sin\theta_{YL} - 1 \quad (2)$$

where $D^* = (d_w + s_w)/d_w$, and d_w and s_w are the filament (wire) diameter and the filament-to-filament spacing, respectively. There are contradictory reports with regards to the accuracy of Eqs. (1) and (2) for apparent CA prediction on wire screens (while studies such as those in [15,40,41] showed good agreement between experimental data and predictions of Eqs. (1) and (2), the work of [17,42] report to the contrary). It is important to note that these equations were derived assuming that (*i*) droplet size is larger than the scale of surface roughness, (*ii*) the surface is isotropic surface, and (*iii*) the AWI is flat. More specifically, Eq. (1) is not derived for when the AWI penetrates into the