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Failure pressures and drag reduction benefits of superhydrophobic wire screens

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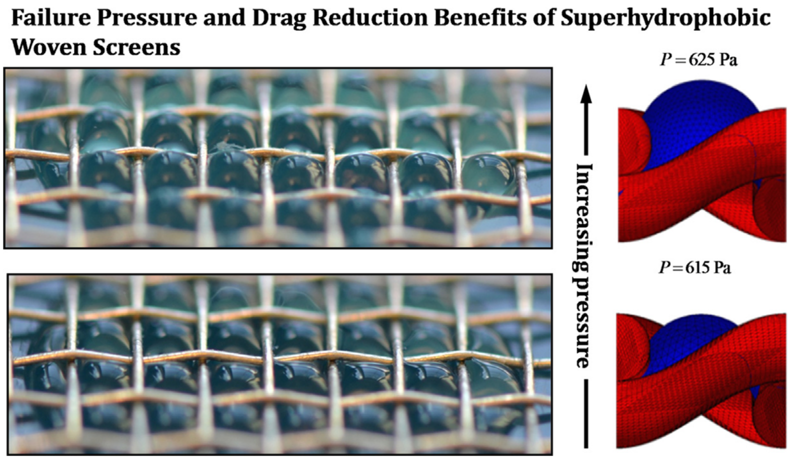
HIGHLIGHTS

- Failure pressures for different superhydrophobic wire screen are obtained.
- Numerical and experimental results are in relatively good agreement.
- Screens' wetted area are obtained as a function of hydrostatic pressure.
- Drag reduction benefits of SHP wire screens are predicted.
- Drag reduction benefits are not affected by hydrostatic pressure.

GRAPHICAL ABSTRACT



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ABSTRACT

This work presents a detailed study on the failure pressure of spray-coated superhydrophobic wire screens in terms of their geometric and wetting properties. Such information is needed in designing fluid–fluid or fluid–air separation/barrier media as well as drag reducing and self-cleaning surfaces, amongst many others. Good agreement has been observed between the results of our numerical simulations and the experimental data for failure pressure. In addition, the wetted area of the screens was calculated and used to predict their drag reduction benefits when used in a Couette flow configuration under different operating pressures. Interestingly, it was found that operating pressure in the Couette configuration does not significantly affect the drag reducing effects of the screens.

Abbreviations: AWI, air-water interface; CHP, critical hydrostatic pressure; PBC, periodic boundary conditions; SE, surface evolver; YLCA, Young–Laplace contact angle.

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Nomenclature

A	Area
A_w	Solid wetted area fraction
$\bar{b}_{app}$	Approximate effective slip length
$\bar{b}_{up}$	Effective slip length calculated using shear stress at the upper plate
$\bar{b}_{flat}$	Effective slip length for a flat interface
d_w	Wire diameter
E	Energy
$f(x)$	Sinusoidal function
g	Gravitational acceleration
h	Manometer height
H	Gap distance in couette flow
l_w	Center-to-center distance between wires
N	Total number of volume mesh
p	Pressure
P_{sag}	Sagging pressure
P_{brk}	Breakthrough pressure
s_w	Spacing between two consecutive wires
$\bar{u}$	Magnitude of slip velocity
α	Immersion angle
δ	Distance from the top of the screen wire and the flow domain
ε	Aspect ratio of screen
θ	Young–Laplace contact angle
ρ	Density
σ	Surface tension
τ_{flat}	Area-weighted shear stress in couette flow
τ_{slip}	Area-weighted shear stress over a SHP surface
φ	Phase angle in radians

1. Introduction

Superhydrophobic (SHP) surfaces, often produced by incorporating single or multiscale roughness into a hydrophobic material, are known for their ability to reduce the area of contact between water and the solid surface (referred to here as the wetted area). The reduced wetted area, in turn, brings about peculiar attributes that are essential for applications such as self-cleaning [1–3] and drag-reduction [3–7] to name a few. Given the prohibitive cost associated with large-scale production of microfabricated SHP surfaces, woven screens enhanced with functional surface treatments/coatings have recently been considered as a cost-effective alternative in many applications requiring a SHP surface. SHP woven screens can be used for drag reduction [8–11], oil–water separation [12–16], self-cleaning and anti-icing [17–19], underwater protection of electronic devices [20,21], water harvesting [22], and heat transfer [23] among many other applications. There have also been interesting studies on the load-carrying properties of SHP wire screens for device manufacturing [24–28].

Performance of a SHP surface depends on the mechanical stability of the air–water interface (AWI) that forms over the non-wetting pores of the surface upon contact with water. Depending on surface geometry and hydrostatic/hydrodynamic pressure, the AWI can ingress into the space between the wires to allow the Wenzel state (fully wetted), the Cassie state (fully dry), or a series of transition states in between the two extreme states to prevail over the surface. The main forces acting on an AWI are the hydrostatic/hydrodynamic pressure and the capillary pressure (see [29,30] for more detailed information). The hydrostatic pressure at which a SHP surface starts departing from the Cassie state is referred to as the critical hydrostatic pressure (CHP) [29,30]. This definition is often used in the context of pores with sharp-edged entrance where the AWI can anchor (pin) itself to the edges of the pore. The definition is less clear when the pore entrance is round (the case with wire screens). This is because in this case, the AWI cannot anchor itself to any sharp corner, and has to conform to a shape that maintains the Young–Laplace contact angle (YLCA) at any point along the curved walls of the pore. Therefore, even at a zero hydrostatic pressure, it is hard to define a fully dry (Cassie) state. Obviously, the AWI moves further down into the pore in response to any increase in the hydrostatic pressure [17,31–34]. For the lack of a better alternative, we define CHP for a pore with round entrance, to be the hydrostatic pressure at which the AWI moves down into the pore such that the pore's capillary pressure reaches its maximum value (referred to here as the breakthrough pressure) denoted with P_{brk} (see [17,31–34] for more detailed information). Transition to the Wenzel state can also occur if the AWI touches the bottom of the pore under pressure. This has been identified in the literature as failure due to AWI sagging or the lack of "robustness height" [31,35]. For applications in which a wire screen is used as a coating placed on a surface (e.g., [9–12], and [18,19]), we consider sagging to be the failure mechanism and the pressure associated with this pressure is shown with P_{sag}. On the other hand, for applications in which a wire screen operates as a barrier between two different fluids or two different compartments (e.g., [13–17,20–22,24–28]), we consider failure to be the condition where the pressure over the screen exceeds the breakthrough pressure.

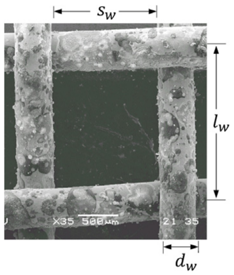

Fig. 1. An example SEM image of the superhydrophobic wire screens considered in the study.

In the remainder of this paper, we first present our numerical approach for predicting the wetted area and failure pressures of SHP wire screens in Section 2. We then discuss our custom-designed setup for testing a screen's breakthrough pressure in Section 3. In Section 4, we present available expressions for calculating the slip length over a SHP wire screen. Finally, our results and discussion are given in Section 5 followed by our conclusions in Section 6.

2. Predicting wetted area and failure pressures

In our simulations, sagging pressure, breakthrough pressure and slip length are calculated for simple square-weave wire screens (same number of wires per unit length in both directions). These screens are generally described by the geometric parameters: spacing between the wires s_w, diameter of the wires d_w, and the center to center distance between the wires l_w, as can be seen in Fig. 1. The Surface Evolver (SE), finite element code, is used in our study to determine the shape and position of the AWI under elevated hydrostatic pressures [36]. The screen is simulated by modeling a unit cell of the repeating geometry using symmetry boundary conditions on the planes slicing through the center line of the consecutive wires