Droplet Behaviour on Metastable Hydrophobic and Superhydrophobic Nonwoven Materials

Abstract

Wetting is the most fundamental interaction between a solid and a liquid that modulates the spreading of the liquid through a balancing act of adhesive and cohesive forces. A hydrophobic surface is formed when the cohesive forces between the liquid molecules are stronger than the adhesive forces that exist between the liquid and solid molecules. Introducing nano- and/or micro-scale roughness on a hydrophobic surface or, alternatively, a micro/nanostructured rough surface coated with a hydrophobic layer tends to form a superhydrophobic surface. The macroscopic contact angle of a water droplet on the regular surfaces in the form of pillars and posts is well-understood and has been quantified in the literature. However, nonwoven materials consist of disordered and irregular arrays of fibres, bonded by friction and/or cohesion and/or adhesion. These materials have been sporadically investigated theoretically for the metastable and superhydrophobic states of the liquid droplet. Unfolding the intricate three-dimensional (3D) structure of nonwoven materials is a prerequisite to obtain the structural parameters that can serve as key inputs for predictive modelling. In this research work, a roadmap to gain insights into the metastable hydrophobic and superhydrophobic states of the liquid droplet on various nonwoven materials and their self-similar counterparts is presented by formulating a toolbox of analytical models. Key design parameters in the form of roughness factor and area fraction of fibres in contact with the liquid have been quantified.

With the aid of X-ray micro-computed tomography (micro-CT) analysis, the fibre and structural parameters, including fibre diameter, pore-size distribution, nonwoven porosity, and fibre orientation distribution, have been quantified. Some of these structural parameters served as key inputs for predicting the apparent contact angle in the metastable hydrophobic state of the liquid. The metastability of the wetting state is also confirmed via the highly diverse behaviour of water droplets ranging from rolling off or gradual absorption at various inclination angles to strong adhesion. Various combinatorial strategies to obtain hybrid wetting regimes have been designed and developed based upon self-similarity. A facile, scalable, and inexpensive vacuum filtration process has assisted in creating self-similar arrays of multi-

walled carbon nanotubes (MWCNTs) and nonwoven fibres. A simple analytical model has been proposed to predict the apparent contact angle by formulating a direct relationship with the structural parameters of MWCNTs and nonwoven materials. In general, a satisfactory agreement has been observed between the theoretical and experimental apparent contact angles of MWCNT decorated nonwoven materials.

On the other hand, spray-coating has been utilised to decorate the weakly hydrophobic stearate-treated titanate nanowires (TiONWs) on the surface of the nonwoven material. This has led to the self-similar nonwoven-titanate nanostructured materials (SS-Ti-NMs) that resulted in a superhydrophobic effect (contact angle >150^o with roll-off angles in the vicinity of 10^o). In SS-Ti-NMs, the 3D nonwoven material houses the air pockets in the bulk of the material along with the water repellent TiONWs on the surface resulting in superhydrophobic behaviour. Laser scanning confocal microscopy has confirmed the presence of a thin layer of water on the finer fibre SS-Ti-NMs. The governing design principles that underpin the key determinants responsible for the robust superhydrophobic behaviour have been unravelled. A comparison between theory and experiments has resulted in a good agreement. The present work also uncovers a wettability gradient across the thickness of SS-Ti-NMs in addition to the unusual display of underwater superhydrophobic behaviour. The current research work paves the way for several unexplored possibilities of nonwoven applications in the fields of energy storage, sensing, protective and biocidal garments, flexible and low-cost chemically active systems, and many more.

Link to Ph.D viva :

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