Colloids and Surfaces A: Physicochem. Eng. Aspects 467 (2015) 31–45

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa

Impact of aqueous suspension drops onto non-wettable porous membranes: Hydrodynamic focusing and penetration of nanoparticles

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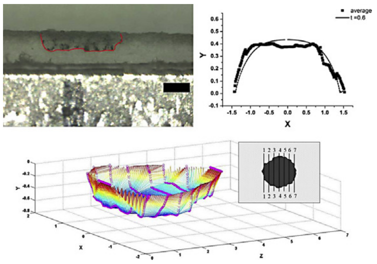
HIGHLIGHTS

- Impact and penetration of nanoparticle suspension drops into porous membranes.
- Hydrodynamic focusing dominates other effects and water penetrates into membranes.
- Deposition patterns of seeding nanoparticles inside the membranes were observed.
- Theory for dynamic penetration of liquid in porous media due to drop impact is proposed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 September 2014
Received in revised form
10 November 2014
Accepted 12 November 2014
Available online 20 November 2014

Keywords:
Drop impact
Hydrodynamic focusing
Penetration front
Nanoparticles
Coalescence filters

ABSTRACT

The impacts and dynamic penetration of nanoparticle suspension drops into porous filter membranes are studied experimentally and theoretically. This type of penetration is associated with hydrodynamic focusing and is radically different from the wettability-driven imbibition. In the case of hydrodynamic focusing water can penetrate into a non-wettable porous medium at very low values of the dynamic pressure associated with drop impact. Two types of membranes are used in the experiments: (i) glass fiber filter membrane wettable by the carrier fluid (water), and (ii) polytetrafluoroethylene (PTFE) depth filter membrane, non-wettable by the carrier fluid. The nanoparticle entrainment and deposition inside the membrane bulk is used to mostly visualize the ultimate penetration fronts by observing the cut cross-sections of the membranes, albeit also provide an insight into innovative applications like circuit printing on nonwovens. The deposition patterns inside the membranes are also linked to the drop splashing patterns at their front surfaces. The experimental results confirm that during the dynamic focusing water can penetrate into a non-wettable porous medium (PTFE). Water also penetrates by the same hydrodynamic focusing mechanism into the wettable glass fiber membrane, where it additionally spreads on a much longer time scale due to the wettability-driven flow. A theory explaining hydrodynamic focusing penetration of liquid into porous medium after drop impact is proposed. It is used to explain and predict water penetration into the non-wettable filter medium after drop impact, and the results are compared with the experimental data. Also the critical thickness of non-wettable membranes determined by dissipation of the kinetic energy in flow inside membrane is evaluated and compared with the experimental data.

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http://dx.doi.org/10.1016/j.colsurfa.2014.11.023
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1. Introduction

Drop impact and spreading on impermeable solid surfaces and porous media are characteristic of numerous applications and are a part of our everyday experience [1]. The observations made with the help of high-speed cameras revealed many intriguing features of drop impact onto solid, liquid and porous surfaces [1–8]. Recently it was shown that drop impacts at velocities about 3.5 m/s onto nano-textured electrospun membranes can result in water penetration even through hydrophobic Teflon nanofiber mats, i.e. the hydrodynamic focusing effects can fully dominate the wettability effects [5]. During hydrodynamic focusing the kinetic energy brought by a drop which impacts a wall with a very small opening in comparison to the drop size is focused into the opening, which results in very high initial speeds of flow into it. This effect is related to the well-known formation of shaped-charge jets (the Munroe jets or the Neumann effect) due to focusing of the kinetic energy delivered by an explosion to a ductile metal (a liner on the explosive conical cavity which collapses), when the metal flows with very high speed like an inviscid liquid through a tiny opening [9]. A similar hydrodynamic focusing in the form of jetting (an ejecta sheet) was predicted in the neck between an impacting droplet and the target liquid surface [10], which was confirmed in the experiments in the subsequent work [11]. Due to the hydrodynamic focusing, the initial velocity of liquid penetration into individual pores $U_p \approx \left(D/d\right) V_0$ is several orders of magnitude higher than the drop impact velocity V_0, since the drop size D, which is of the order of 1 mm, is much larger than the pore size d, which is of the order of 1 μm [4,7]. During the hydrodynamic focusing, the initial penetration velocity U_p is much larger than the Lucas–Washburn velocity corresponding to the wettability-driven imbibition, which makes the latter immaterial, while water drops are penetrating into Teflon electrospun nanofiber mats [5]. Moreover, the hydrodynamic focusing resulting in dynamic penetration happens well below the static penetration threshold, i.e. at $\rho V_0^2 < 4\sigma/d$ (with ρ and σ being the liquid density and surface tension), already at $\rho V_0^2/\left(4\sigma/d\right) \approx 0.025$, in distinction from the case when drops and orifices are of the same order of magnitude [12]. The hydrodynamic focusing and penetration of drops into electrospun nanofiber mats has already been used to enhance cooling of high-heat flux surfaces [6], and in particular, to prevent the Leidenfrost effect even at such high surface temperatures as 300 °C [7,8]. The effect of surface roughness of the impermeable non-porous media on drop impact is clearly distinct from the phenomena observed in drop impacts onto permeable porous nano-textured surfaces [1,8,13].

Liquid flow on porous substrates in some cases depends on the liquid/solid wetting properties. Much work has been done on liquid drop spreading on porous substrates in the creeping flow regimes at low Reynolds number $Re < 1$, where the spreading and pore imbibition are governed by the contact line motion, capillary pressure and wettability. Magnetic resonance imaging or X-ray could be possible options for the observations inside porous media, albeit they are either too slow or do not provide enough resolution to observe the evolution of the liquid penetration front. Significant research efforts were directed at the low Reynolds number spreading and wettability-driven imbibition, which was studied experimentally, analytically and numerically [14–20]. These sources provide a wider context for the present work which aims at the observations of liquid penetration into porous media following drop impact. It should be emphasized that drop impact onto nonwoven membranes comprised of multiple fibers encompassing the inter-fiber pores involves simultaneous interaction of liquid with multiple fibers and thus, involves different phenomena compared to those in drop impact onto individual fibers [21,22], since in the latter case hydrodynamic focusing is impossible.

Modeling of flow within porous media can be quite challenging, particularly in the case of multi-phase (liquid, gas and/or vapor) flows [23]. Properly depicting the pore topology is essential for such simulations. Among various methods available for the observations of pore structures, micro-CT (micro-computed tomography) imaging technique is the most recent. It provides a direct visualization of the pore geometry [24]. On the other hand, numerical modeling of forced impregnation of a single or a few capillaries tackled only the regimes with $\rho V_0^2 \gg 4\sigma/d$ and is irrelevant in the present context, as discussed below.

Forced penetration of a single liquid drop through both hydrophilic and hydrophobic capillaries has been experimentally observed to delineate different impregnation regimes [25]. The drop diameter corresponding to the maximum spreading is very important because it elucidates the conditions under which the penetration process begins [26]. Refractive index matching technique was used to track the kinetics of drop penetration into porous medium [4]. One of the main parameters governing liquid penetration into pores under the almost static conditions is the capillary pressure based on the pore size and wettability [12]. The rate of imbibition of porous media and spreading over the surface was estimated by measuring the change in the contact radius and height of the drop [27].

Coalescence filters are an example of porous media collecting drops from an oncoming gas or liquid flow [28–30]. Drops penetrate the filter membrane and accumulate inside. As a result, filter permeability decreases, whereas the pressure drop in gas which is required to sustain the flow increases. Some groups expressed expectations that a hydrophobic filter medium will prevent water drops from penetrating inside, thus facilitating water collection and removal at the front surface. The hydrodynamic focusing, however, is expected to overcome hydrophobicity and let the impacting water drops to penetrate into hydrophobic media [4–8]. In the present work this is directly demonstrated using the entrainment of seeding nanoparticles. In a broader context, the entrainment of seeding particles is not merely an observation tool but is of interest by itself in such applications as inkjet printing on smart textiles [31].

The aim of the present work is in the experimental and theoretical investigation of dynamic liquid penetration due to hydrodynamic focusing, and the entrainment and deposition of nanoparticles suspended in drops impinging onto a porous filter membrane. In Section 2 the experimental details are given. Then, in Section 3 the experimental results are presented. The theoretical framework is described in Section 4. The discussion and comparison of the predictions with the experimental data are presented in Section 5, where also the critical thickness of non-wettable membranes is elucidated. Conclusions are drawn in Section 6.

2. Materials and methods

2.1. Materials

Glass fiber filter (1 mm thick and 47 mm in diameter) with 2.7 μm pores and polytetrafluoroethylene (PTFE) depth filter (1 mm thick, 47 mm in diameter) with 10 μm pores were purchased from Cole-Parmer and used as received. Glass fiber membrane is wettable with water, whereas PTFE is non-wettable. The surfaces of the membranes were observed using optical microscope Olympus BX-51 (Fig. 1). They are nonwoven fibrous materials. The glass fiber filter reveals distinct pores and fibers (Fig. 1a–c), whereas the PTFE filter reveals some film-like structures with open pores attached to fibers (Fig. 1d–f). The pore size is determined by the particle size that will be retained with 100% efficiency under specified conditions. The pore size of the membranes used in the present work was specified by the supplier as 2.7 μm for the glass fiber filter