Current Opinion in Colloid & Interface Science 19 (2014) 320–335

Contents lists available at ScienceDirect

Current Opinion in Colloid & Interface Science

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

Liquids on porous layers: wetting, imbibition and transport processes

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ARTICLE INFO

Article history:
Received 16 January 2014
Received in revised form 1 September 2014
Accepted 2 September 2014
Available online 6 September 2014

Keywords:
Spreading
Imbibition
Porous media
Wetting transition
Nanofiber mat
Heat transfer enhancement
Cooling
Particles deposition

ABSTRACT

Wetting of porous layers plays an important role in natural phenomena and in technical applications, including cooling technologies, ink-jet printing, functionalization of textile fabric and 3D-printing. In many technically relevant processes the complex wetting phenomena govern the transport of heat, mass and (nano)particles. A review of recent advances in understanding and development of prediction tools describing the coupled wetting and transport in porous layers is given. A special focus is laid on fibrous media, which are frequently encountered as natural substances (human hair), as conventional technological products (textile fabric) or as promising method for heat transfer enhancement (nanofiber mat coating of surfaces). The possible directions of future research are suggested.

1. Introduction

Understanding the wetting of porous substrates by liquids, the liquid imbibition into porous layers and concomitant transport processes is important for many industrial applications, including ink-jet printing, 3D-printing, penetration of rain drops into building walls, needleless injection, coating of porous materials, irrigation, cooling of electronic devices. Recently, the interest to interaction of liquids with porous and textured surfaces has been increased, since they are promising as superhydrophobic and superamphiphobic surfaces [1,2].

Wetting of porous layers and imbibition are complex processes depending on the physical and chemical properties of the solid and the liquid, the geometry of the porous structure and the thickness of the layer [3]. The phenomena taking place during droplet spreading over porous media are schematically represented in Fig. 1.

Depending on the properties of the substrate and the liquid, droplets over porous layers may display different types of behavior, including non-wetting behavior, spreading over the surface of porous layer, as well as vertical and lateral imbibition into the layer. The interaction between the liquid and porous substrate is generally governed by dynamic wetting [4] and imbibition [5–7], which are often competing processes, with their relative importance determined by the relation of the respective time scales. If the porous medium includes nanoscale pores or nanoparticles, the influence of conjoining/disjoining pressure plays an important role [8]. If the liquid spreading over a porous layer is volatile, evaporation may bring about additional effects significantly changing the wetting state [9,10]. If the drop hits the substrate with a non-zero velocity, the liquid penetrates into the pores by inertia. The velocity of the dynamic pore filling may significantly exceed the impact velocity, if the pore size is much smaller than the droplet size [11,12]. Additionally, the flow of liquid through the porous layer not supported by impenetrable substrate can be induced by mechanical pumping [13].

Lateral imbibition may take place not only in porous layers, but also on rough or textured surfaces which can exert a capillary action [14]. Typical structures of porous or textured layers which are encountered in practice or used as model surfaces in research are schematically represented in Fig. 2. In Fig. 2a an isotropic open-porous structure is presented. A structure comprised of spherical particles is shown in Fig. 2b. This structure is also isotropic. In Fig. 2c a substrate containing cylindrical unidirectional non-interconnected pores is represented. This is evidently an anisotropic structure which of course does not allow any lateral imbibition (imbibition in the direction normal to the pores axes). A substrate decorated with cylindrical pillars is shown in Fig. 2d. Finally, a substrate coated by a (nano)fiber mat (fibers aligned parallel to the substrate plane) is shown in Fig. 2e. This structure possesses significantly different transport properties in direction parallel to the fibers in comparison with the properties in normal direction.

Porous media and porous layers can be classified according to their saturation with penetrating liquid. In dry porous media the whole pore volume is filled with air, in saturated porous media all pores are filled with liquid, and, finally, in partially saturated porous media,

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http://dx.doi.org/10.1016/j.cocis.2014.09.001

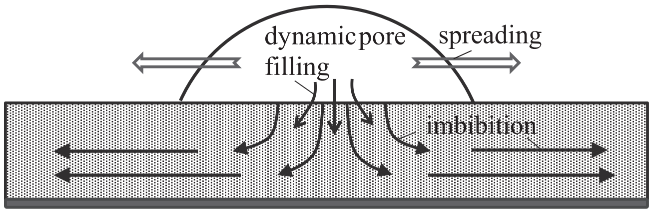

Fig. 1. Schematic representation of phenomena taking place during a droplet spreading over a porous layer.

some of pores are filled with liquid, or, alternatively, some pores are partially filled. In the partially saturated porous media the liquid can constitute isolated areas or a percolating network.

Heat and mass transport during spreading and imbibition of liquid droplets bring new degree of complexity and new time scales into the process. Numerous technically highly relevant processes, such as heat transfer enhancement by using structured or porous substrates, or transport and deposition of particles or caring substances onto fabric fibers, depend on wetting and imbibition hydrodynamics. At the same time the transport processes may influence the hydrodynamics of wetting and imbibition.

The present review discusses the progress in experimental and numerical studies of wetting and imbibition of porous media, layers and coatings (Section 2.1) and the relevant processes on the scale of a single pore or fiber (Section 2.2). Detailed knowledge of the micro- and nanoscopic processes taking place on the scale of single elements or element groups of the porous structure is necessary for understanding of wetting, imbibition and transport processes on the macroscopic scale. In some of the works presented in Section 2 evaporation plays a certain role in fluid transport. Section 3 is devoted to heat transfer and phase change, especially for cooling applications. Since the investigations of heat transfer coupled with wetting of porous layers are relatively rare (although extremely promising for heat transfer enhancement), several works dealing with the heat transfer enhancement on textured surfaces have been included into the review. Discussion of these works helps to elucidate the physical mechanisms affecting heat transfer enhancement and to identify the existing unresolved issues. Section 4 is devoted to a brief review of works on particles deposition accompanying wetting of porous media and some further applications. A special focus is laid on (nano)fibrous materials. The review is concluded by a brief summary and a suggestion of focuses for the future research (Section 5). The influence of surfactants on the spreading process and the effect of fluid mixtures are beyond the scope of the present review.

2. Wetting and imbibition

2.1. Porous media, layers and coatings

In the Subsection 2.1.1 the physics of imbibition is briefly discussed. After that wetting states which can be observed on porous or textured layers are described and discussed (Subsection 2.1.2) with a focus on mechanisms forcing the liquid penetration into the layer in the cases where the liquid initially does not penetrate spontaneously into the porous structure. Subsection 2.1.3 is devoted to discussion of simultaneous spreading and imbibition of liquid droplets into porous layers and coatings.

2.1.1. Physics of imbibition

The simplest case of imbibition is a spontaneous liquid penetration into a cylindrical capillary tube brought in contact with a liquid pool (Fig. 3a). It is assumed that the tube diameter is smaller than the capillary length $\sqrt{\gamma/(\rho g)}$, where γ is the surface tension, ρ is the density of the liquid and g denotes the acceleration of gravity. The capillary length for water at a room temperature at terrestrial conditions is around 2.7 mm. Apart from the initial and the final stages of imbibition, the dynamic of this process is governed by the balance between the capillary and viscous forces. The capillary pressure at the liquid-gas interface is given by the expression $p_c = \gamma \cos \theta/a$, where θ is the equilibrium contact angle and a is the inner radius of the tube. The Poiseuille parabolic velocity profile can be assumed for the flow in the tube far from reservoir. The average liquid velocity can be computed from the following relation:

$$u_{av} = \frac{dl}{dt} = -\frac{\partial p}{\partial z}\frac{a^2}{8\mu} = \frac{\gamma \cos\theta}{l}\frac{a}{8\mu}, \tag{1}$$

where l denotes the meniscus height and μ is the dynamic viscosity of the liquid.

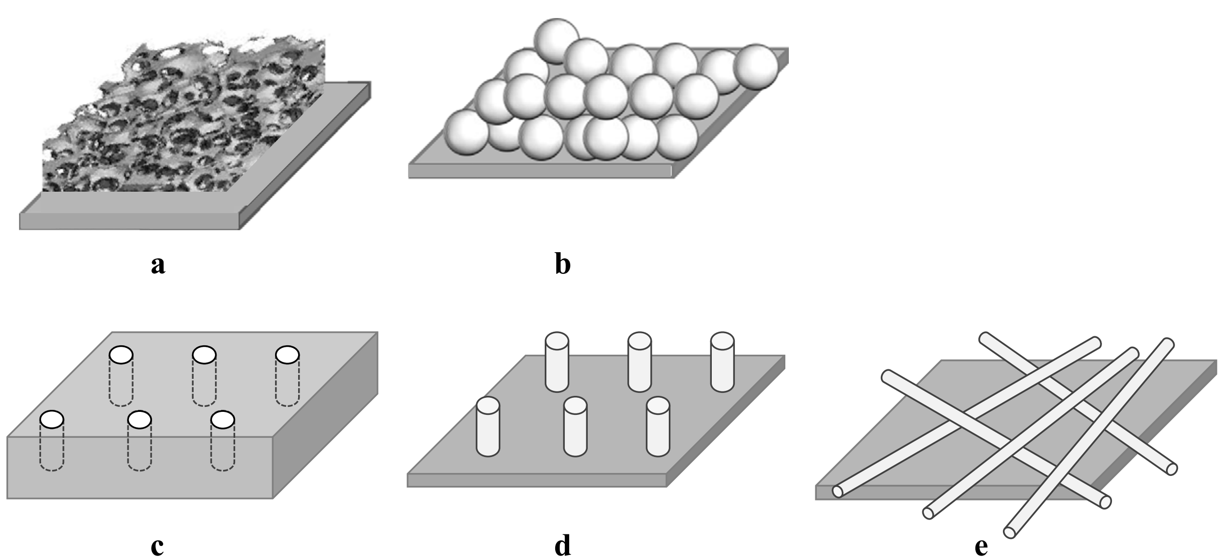

Fig. 2. Schematic representation of porous structures. (a) Isotropic open-porous structure; (b) isotropic structure comprised of spherical particles; (c) anisotropic porous structure with pores in the form of straight channels without interconnection; (d) array of pillars; (e) fiber mat.