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Correlation between shape, evaporation mode and mobility of small water droplets on nanorough fibres

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ABSTRACT

The dynamic wetting behaviour and the mobility of droplets on fibres is a very important factor in coating processes, textile fabrication, in self-cleaning processes and in the filtration of fluids. In principal, filter regeneration depends on the mobility of the droplets on the fibre surface. Mobile droplets tend to coalesce which greatly simplifies their removal from the filter. In this contribution mobility analyses of water droplets on monofilaments in air are performed. Studies of droplet evaporation on pure PET fibres and on nanorough fibres coated with SiO_2 nanoparticles of diameters between 6 nm and 50 nm in a hydrophilic binder system were done. We show that the mobility of water droplets correlates with the droplet conformation which in turn is determined by the droplet–fibre interface. We demonstrate that fibre coatings can be used to tailor the conformation and mobility of water droplets. The smaller the nanoparticle diameters in the coating are, the smaller are the contact angles between water droplets and fibre and the better is the mobility of the droplets on the fibre. Our results allow a fast optimization of the fibre surface properties which are directly influencing the contact angle, the mobility and the coalescence of water droplets and thus filter regeneration.

1. Introduction

Over the last years the wettability of fibres has become more and more important in many industrial areas such as coating processes, textile fabrication, self-cleaning processes and especially the filtration of fluids. Applications are the separation of water droplets from diesel fuel or the vapour-phase deposition of water- and oil droplets out of compressed air by fibre filters. In fluid filtration the droplet transport towards the fibre surface and the dynamic wetting behaviour are crucial. Whereas the impaction of droplets on fibres is well understood, the regeneration of the droplets in fibre filters remains elusive. Basically the regeneration of coalescing filters depends on the mobility of the droplets on the fibre surface: mobile droplets tend to coalesce leading to larger droplets and hence simplifies their removal from the filter.

Due to the cylindrical shape of the fibre, the wetting behaviour of droplets on fibres differs from the wetting of flat surfaces. Early studies on the wetting phenomena of droplet-on-fibre systems have reported on determining the droplet shape and on extracting the contact angle accurately [1]. A fluid that forms a completely wetting film on a flat surface (vanishing contact angle) may not completely wet a fibre of the same material. In the case of flat surfaces, the spreading pressure, $S = \gamma_{sv} - (\gamma_{sl} + \gamma_{lv})$ where γ is the interfacial tension, determines whether a film or a macroscopic droplet with a non-zero contact angle is formed [2]. In case of fibres, a film only forms when S exceeds a finite positive value dependent on the fibre radius. A vanishing contact angle can be consistent with a macroscopic droplet [2–6]. Wagner et al. studied the spreading of liquid droplets on cylindrical surfaces [7]. Yamaki and Katayama describe a theoretical method to calculate the contact angle by observing the shape of a liquid drop attached to a monofilament and point out that the shapes of droplets attached to monofilaments change depending on liquid volume. Moreover, it was found for very small droplets that the effect of gravity is negligible [8]. Carroll studied properties of fluid droplets on cylinders, such as the equilibrium conformation of droplets, contact angles and the stability of small droplets [1,9–11]. Depending on the fibre radius, the droplet volume and the surface energy of the fibre, he found two fundamentally different conformations of macroscopic droplets: i.e. barrel and a clam-shell conformation (see Fig. 1). At the critical contact angle a change of droplet conformation takes place. This 'roll-up'-process results in a change of the contact area which leads to a significant change of the droplet profile. The critical contact angle depends on the fibre radius and the surface energy of the fibre. The most complete experimental data on the roll-up-process was given by Carroll [9]. Barrel shapes occur for large droplets relative to the fibre radius or for low contact angles. Clam-shell shapes occur for small droplets or high contact angles.

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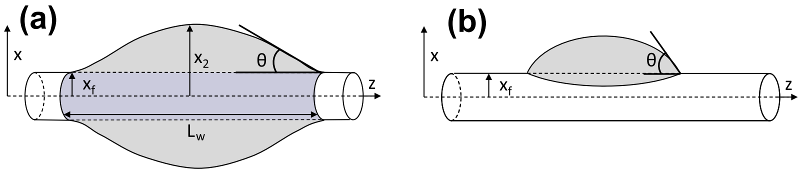

Fig. 1. Conformations of water droplets on a cylindrical fibre [10]: (a) barrel-type; axially symmetric and (b) clam-shell-type; non-symmetric.

In a coalescing filter it is desirable that droplets have a high radial adhesion and a low axial adhesion to the fibre. Droplets of the barrel-type have a bigger radial adhesion to the fibre compared with the clam shell shape droplets and thus the residence time and the probability of droplet coalescence on the fibre is increased. In addition, the clamshell droplet has a longer three phase contact line with the fibre, compared with the relatively short contact line of the barrel conformation. The surface tension force along the fibre is hence relatively small for the barrel shape droplet compared to the clamshell droplet. Thus, the barrel shaped droplets are more likely to slide down the fibre. This demonstrates the highly improved drainage of barrel droplets down the fibre due to a connecting film between the droplets compared to clamshell droplets. Therefore the barrel droplets have a better axial mobility on the fibres at higher residences time, which leads to an increased coalescence, to larger droplets and simplifies the removal of the droplets from the filter [9,12]. Clam shell droplets roll axially on the fibre which increases the probability of leaving the fibre before coalescing with other droplets while barrel droplets slide [13]. Therefore, they are the preferred conformation in coalescing filters.

Also in wet filters a good wetting of the fibres is required [30]. In this case the particles are captured by a liquid film rather than being directly captured by the fibres. Therefore barrel droplets or film formation of the liquid on the fibres is desired in this technique.

The symmetrical drop conformation is characterized by two linear, dimensionless parameters, the reduced drop diameter $n = x_2/x_1$ and the reduced drop length $\text{Ł} = L_w/x_1$. L_w describes the droplet base diameter, x_1 the fibre radius and x_2 the drop height (see Fig. 1). The three parameters can be directly obtained from a photomicrograph ([1,10,11]).

In this publication the influence of the fibre roughness on the contact angle and on the mobility of droplets on fibres is studied. As the mobility of droplets on fibres is determined by the mobility of the three-phase-contact line [14] an analysis of the evaporation behaviour of droplets on fibres is performed as well. Upon evaporation the three-phase contact line of the droplet must shift.

Various studies of the evaporation behaviour of droplets on flat surfaces exist [15–21]. McHale and Newton [17–19] investigated the adsorption and evaporation of droplets on flat surfaces by video microscopy. For initial contact angles less than 90°, the contact area remains constant upon evaporation. In case of structured surfaces a stepwise contraction of droplets depending on the surface structure was observed. Water droplets on textured surfaces evaporate in a stick-slip mode.

Few studies concerning the evaporation behaviour of droplets on fibre surfaces are known [22,23]. Murarova et al. functionalised the fibre surface by pigments via a sol–gel procedure [24]. They found a dependence of the contact angle on time. Mullins investigated the wetting process during filtration of droplets in air [21]. They observed adsorption of water droplets on glass fibres, oscillatory droplet motion and detachment or flow of these droplets along the fibre.

Mobility and coalescence of droplets were investigated on flat and on curved surfaces [25–30]. Bitten et al. found that the maximum diameter of droplets adhering to the fibre surface depends strongly on the fibre material [25]. Mullins et al. studied the influence of fibre orientation on the fibre wetting process and flow of liquid droplets along filter fibres [12]. By determining the forces acting on a droplet on a fibre, it is possible to determine an optimum angle such that the flow of droplets down the fibre will be maximized ensuring maximal filter self-cleaning. Dawar et al. proposed correlations of the droplet mobility as a function of drop and fibre sizes and on the Reynolds (Re) and Capillary (Ca) numbers [14,31]. Mead-Hunter et al. present a theoretical model describing the force required to move coalesced liquid droplets of two different oils along an oleophilic filter fibre and determine the influence of droplet displacement perpendicular to the fibre on the force required to move the droplet experimentally. Additional it was found that fibre surface inhomogeneities strongly influence the results [13,29].

The wetting of flat textured surfaces can be described by two different models, i.e. the Wenzel model and the Cassie–Baxter equation. The Wenzel model describes the homogeneous complete wetting regime and is defined by the following equation:

$$\cos\theta_W = r \cdot \cos\theta \tag{1}$$

In this equation the apparent contact angle θ_w depends on the surface roughness r which is defined as the actual, rough surface area divided by the projected surface area. θ is the equilibrium contact angle on a smooth surface exhibiting the same surface chemistry as the structured surface [32].

If air is assumed to be entrapped in the voids of a rough surface, the contact angle on the rough surface can be described by the Cassie–Baxter equation.

$$\cos\theta_{CB} = r \cdot f_s \cos\theta + f_s - 1 \tag{2}$$

f_s is the fraction of the solid surface area wetted by the liquid [33] and θ_{CB} the contact angle on the rough surface. It is important to realize that when $f = 1$, the Cassie–Baxter equations becomes the Wenzel equation. For water droplets the Cassie–Baxter case generally occurs on hydrophobic surfaces and the Wenzel case on hydrophilic surfaces as in the present case.

Several fundamental questions concerning the influence of surface roughness of fibres on droplet mobility are not sufficiently understood. This contribution shows that the droplet mobility on coated fibres correlates with the droplet conformation on fibres and the wetting behaviour of fibres. As the droplet conformation is determined by the droplet–fibre interface the wetting behaviour of PET fibres was tailored by a surface coating with silica nanoparticles of different sizes embedded in a hydrophilic binding system. The coatings, including nanoparticles, create a certain fibre surface roughness, depending on the nanoparticle diameter.

2. Materials and methods

2.1. Preparation of the fibres

For the analysis of the wetting and the evaporation behaviour of water droplets in air PET fibres (diameter 100 μm) were coated with a hydrophilic binding system excluding and including SiO_2