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Movement of a liquid droplet within a fibrous layer: Direct pore-scale modeling and experimental observations

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HIGHLIGHTS

- Spreading and penetration of a droplet on paper were simulated using a pore-scale model.
- The effect of change in contact angle and ink physical properties were studied.
- Contact angle of zero showed largest penetration and no moving away from jet location.
- Ink-like liquid moved slower than water droplet and its penetration depth was smaller.

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ABSTRACT

In this study, the spreading of a liquid droplet on the surface of a fibrous paper and its penetration into the paper is studied. The spreading of the droplet was visualized using confocal microscopy and the penetration depth was quantified using Automatic Scanning Absorptiometry (ASA) measurements. The three-dimensional structure of the paper was obtained through micro-tomography imaging with a resolution of 0.9 μm. The obtained images were used to reconstruct the pore space, which was in turn used in direct numerical simulations of penetration of a droplet into paper. Simulations were performed using open source code OpenFOAM, which solves equations of two-phase flow (in our case air and water) in pores based on the Volume of Fluid Method. Simulation results showed a good agreement with the experimental observations. In particular, the dimensions of spreading area of a droplet and the depth of penetration were simulated reasonably well. Then, we used the model to investigate effects of changes in various liquid properties on spreading and penetration of a droplet liquid. We made calculations for three different values of contact angle (*CA*): 0 °C, 60 °C, and 120 °C. We found the largest penetration depth for *CA* = 0. For *CA* = 60 and *CA* = 120, we found that the liquid droplet moved sideways from the jetted location, which is not favorable in inkjet printing. We also made simulations with larger values for viscosity and density, based on properties of an ink-based liquid used in inkjet printing. The results have shown a slower spreading and penetration compared with water. The model can be used to study effects of changes in either ink physical properties or paper layer microstructure on final spreading/penetration extent.

1. Introduction

Cellulose fibers are renewable natural materials, which are encountered in many industrial applications, such as paper and printing, packaging, and paper-based diagnostic devices. Their main features important to these applications are light weight, mechanical strength, and low cost (Podsiadlo et al., 2005).

In the majority of applications, a fibrous layer comes into contact with some liquid (mainly water-based liquid). Because cellulose fibers are hydrophilic, liquid will move rapidly along and into fibers. This can cause unwanted spreading of ink in paper, for example in case of inkjet printing (Fig. 1), or swelling of fibers, which can be a problem in the case of packaging application.

Generally, a fibrous layer can be considered as a porous medium, although liquid flow in the layer is different from traditional porous media. Usually, a liquid moves into pores of a porous network and, based on connectivity of pores, invades some of them. However, in the case of a fibrous layer, water moves first on the

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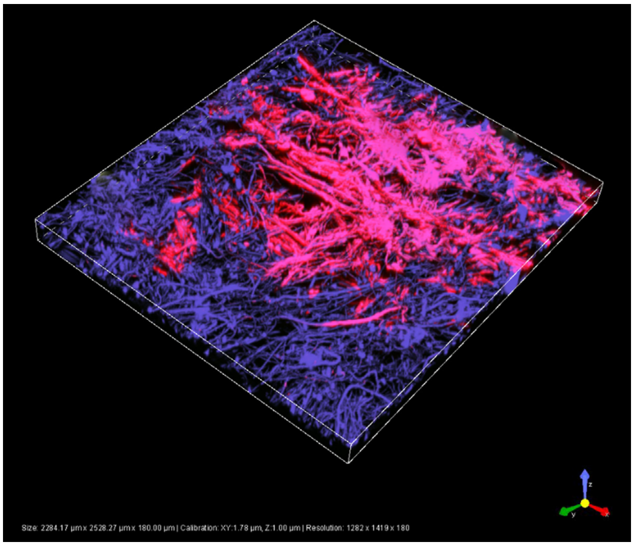

Fig. 1. Water spreading in a fibrous layer; fibers are shown in blue and water in pink. The image was obtained using confocal microscopy.

surface of fibers and/or into them, and then later on fills the pores between fibers (Aslannejad and Hassanizadeh, 2017). Schoelkopf et al. (2000) stated that under a condition of constant wettability and surface energy, pore diameter and geometry are the controlling factors. Therefore, contradictory to Lucas-Washburn equation which predicts the large pores to be filled faster than small pores, liquid droplet in a paper layer proceeds by filling finer pores together with inertial retardation of larger pores and then, viscosity-controlled absorption dynamics becomes prominent. Liu et al. (2017) also considered the difference between coated and uncoated paper from droplet wicking point of view and they conclude that, in case of uncoated paper, the wicking behavior follows neither viscosity-controlled model of Lucas-Washburn nor inertia-included model of Bosanquet. Modaressi and Garnier (2002) also reported such a flow behavior in a partially hydrophobized fibrous layer. They did an experiment and reported that the droplet first imbibed into the fibrous layer forming a pattern in the layer and then when it reached steady state, it was absorbed into the fibers.

In case of inkjet printing, there are two types of paper: plain and coated. Plain papers, made of cellulose fibers, may absorb too much ink. In order to limit ink uptake by plain paper, often a thin layer of coating material is applied on the surface of fibrous layer. However, due to their overall low cost, uncoated papers are more commonly used in inkjet printers. Then, various measures are taken to reduce the uptake of ink and its spreading into the fibrous layer. These relate to the modification of the properties of ink and/or fibers. Effects of such measures have been studied in recent decades. Yarin (2006) studied normal impact of a droplet on dry paper surface and characterized effects of surface roughness, surface texture, and wettability. Modification of liquid properties by adding a polymer mixture was also studied. Xu et al. (2005) reported that by controlling the pressure artificially generated in a gas atmosphere (helium, air, krypton, and SF) during droplet impact on the solid surface, they could control splash of droplet.

Alam et al. (2007) studied the kinetic-energy-driven phase of spreading of a liquid on irregular surface of a porous material using the Volume of Fluid method (VOF). They performed computations and showed that the spreading width is inversely correlated with the depth of penetration. They studied different surface roughness types: flat, randomly located monodisperse hemispheres, and pyramidal structures. Analysis of various roughness parameters and their impact on spreading were done in their work.

Hyväluoma et al. (2006) studied penetration of a liquid in paperboard using Lattice Boltzmann method. They used reconstructed pore space of a sample imaged by micro tomography. Capillary-driven flow into the domain was simulated and compared with well-known Lucas-Washburn equation results. They concluded that there is a need to study and determine advancing of the liquid front into the paper. They also concluded that water penetration occurs along fibers and much faster in the planar direction than in the perpendicular.

Do-Quang et al. (2011) investigated numerically the impact of ink onto the surface of a paper-like structure; they used a model structure as a fibrous web. They simulated multi-phase flow of air and liquid and they determined the penetration pattern of the droplet in the structure. They also studied the impact of change in wettability on penetration.

To the best of our knowledge, there have been little to no direct comparison of spreading of a liquid on a fibrous layer and the degree of its penetration with numerical simulations. In addition, studies involving a liquid with ink-like properties comparable to ink have been limited.

In this study, we focus on not only spreading of a droplet on a paper surface, but also its penetration into the fibrous layer. The fibrous layer pore and fiber structure were reconstructed using high-resolution micro-tomography images. The resulting digitized layer was then used as input in two-phase simulations of penetration of a droplet into the fibrous layer. Simulation results were then compared with experimental results from confocal microscopy and automatic scanning absorptiometry ASA measurements. The effect of wettability change was studied by specifying different values for contact angles. In addition, the effects of change in fluid properties (density, viscosity and surface tension) on resulting penetration/spreading are reported. The results of this study will contribute to a better understanding of the flow in printing paper. By optimizing properties of the liquid and paper, a cheaper production of high quality prints can be made possible. Moreover, results of this research are relevant to the general understanding of interaction of complex fluids with complicated porous structures.

2. Material and methods

2.1. Paper and liquids

A Ziegler uncoated paper sample (Ziegler paper, Switzerland) was used in this study. Fig. 2 shows an SEM image of the cross section and surface of the paper sample. The fibrous layer of paper is

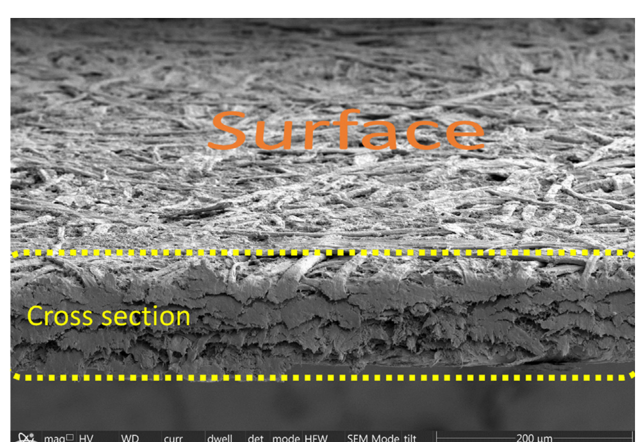

Fig. 2. Three-dimensional SEM image of cross section and surface of a Ziegler paper sample.