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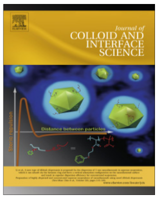

Regular Article

Stick–slip motion and controlled filling speed by the geometric design of soft micro-channels

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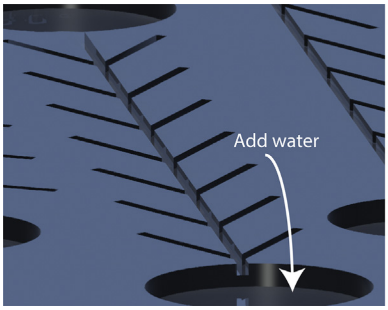
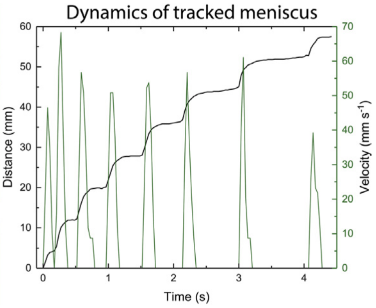
GRAPHICAL ABSTRACT





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ABSTRACT

Hypothesis: Liquid can move by capillary action through interconnected porous materials, as in fabric or paper towels. Today mass transport is controlled by chemical modification. It is, however, possible to direct mass transport by geometrical modifications. It is here proposed that it is possible to tailor capillary flow speed in a model system of micro-channels by the angle, size and position of attached side channels.

Experiments: A flexible, rapid, and cost-effective method is used to produce micro-channels in gels. It involves 3D-printed moulds in which gels are cast. Open channels of micrometre size with several side channels on either one or two sides are produced with tilting angles of 10–170°. On a horizontal plane the meniscus of water driven by surface tension is tracked in the main channel.

Findings: The presence of side channels on one side slowed down the speed of the meniscus in the main channel least. Channels having side channels on both sides with tilting angles of up to 30° indicated tremendously slower flow, and the liquid exhibited a stick-slip motion. Broader side channels decreased the speed more than thinner ones, as suggested by the hypothesis. Inertial forces are suggested to be important in branched channel systems studied here.

1. Introduction

The spreading or moving of fluids is of great industrial importance, for example, in oil recovery, textile processing, and mortar drying, and knowledge of it is also needed in various biomedical applications and diagnostics, such as lab on a chip or lab on a paper [1]. The spreading of water on hydrophilic non-smooth surfaces also occurs naturally in biology and has important functions, for example, in ensuring effective nutritional absorption and the perception of tastes and odours [2].

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A fluid can be moved, for example, in microfluidics, using valves and pumps requiring active work and careful adjustment of the pressure. It needs experienced and skilled personal for Lab-on-a-chip-devices to adjust those parameters to apply an appropriate pressure, which could be rare specifically in developing countries [3]. An easier way to move fluids is to take advantage of capillary action and passively let the liquid flow. Capillary action, or wicking, is driven by the surface forces of the material and the imbibing liquid, and occurs spontaneously when (i) the contact angle between the imbibing liquid and the surface is <90° and (ii) the diameter of the capillary/channel is small enough [4]. Capillary action has been studied and modelled by Lucas [5] and Washburn [6] and can be described by the commonly quoted Lucas–Washburn (LW) equation, which combines the driving force (i.e., capillary pressure) with the opposing Poisseuille flow:

$$x^2 = \frac{\gamma R cos\theta}{2\mu} t \qquad (1)$$

where R is the channel radius, μ the dynamic viscosity of the liquid phase, γ the surface tension of the liquid, and θ the static contact angle of the liquid on the channel wall [5,6].

Wicking and wetting in hard 2D materials are well understood through models and theories [7,8]. Several studies of wicking in differently shaped channels (i.e., V-shaped [9,10], rectangular [11], skewed U-shaped [12], and cylindrical [11]) demonstrate that wicking generally follows LW predictions independent of whether the channels are closed or open. The fluid direction can be controlled by using pillars on a plane (see [13], a numerical study). Wicking in the preferred direction can also be obtained by manipulating the design of structures extending into the channels [14]. The wicking of fluid in open channels offers the advantages of ease of surface modification, ease of cleaning (or, as in the present case, use of disposable systems), and reduced risk of clogging [11]. The only way of filling open channels is by using capillary action and/or wicking, since they cannot be filled by pumping. Although paper-based medical devices hold great potential, they still vary in specificity and sensitivity [1]. Generally only about 50% of the applied test fluid reach the detection zones and their speed greatly influences both specificity and sensitivity. These are still issues to overcome, where the understanding of precise flow dynamics could help to add to the breakthrough of Lab-on-a-paper-devices [3].

Preferred pathways of the imbibing liquid are also observed in interconnected 3D materials characterised by inhomogeneous pore size distributions, such as the paper or sponges used in wound-care products [15–17]. Pore sizes are often hierarchical in that there are pores which can differ one or several magnitudes in size. The exact cause of these preferred pathways is discussed in the literature but is not yet known. One point of discussion has been if large or small pores are filled first in an interconnected porous system [18–21]. Since the liquid flows faster in larger capillaries one can assume that they are also filled first in a porous system. However, capillary pressure is higher in smaller pores so that liquid can also rise higher than in thicker capillaries.

Moreover, in an interconnected porous system, the liquid not only takes a preferred pathway but also moves discontinuously. This means that the meniscus accelerates and decelerates throughout the system, giving rise to increased inertial forces [20] adding up to behaviour deviating from LW equation predictions [17,22]. Sometimes, the liquid even stops and then suddenly resumes movement in what are referred to as Haines jumps [23].

The challenge of investigating such a complex porous system is that of directly tracking several menisci in a 3D porous system. However, systematic studies seeking the cause of such preferred pathways might fail because of the high production costs of precisely defined channels. Channels with controlled size and structures are commonly prepared using photolithography techniques. Photolithography involves the deposition of photoresist on a substrate using a spin coater, and then the manufacture of a master used in exposing the photoresist to UV light with a mask aligner. This causes the photoresist to cross-link in the exposed or non-exposed areas, depending on the type of resist; the resist is subsequently lifted off by a remover. All the involved work must be undertaken in cleanroom facilities. While such techniques allow precise control of the channels, they are costly and time consuming. A low-cost alternative to the lab-on-a-chip approach is the application of microfluidics on paper in the lab-on-a-paper approach [1,24]. Photolithography (which physically blocks the pores in the paper), ink-jet printing (which chemically modifies the fibre structure), and wax printing (which physically deposits reagent on the fibre surface) are used to control fluid movement in lab-on-a-paper applications.

Wetting and therefore wicking are more complex in soft materials than hard materials [25,26] because local deformation of the soft material occurs near the contact line [27,28]. We have previously reported that capillary filling in soft hydrophilic capillaries is in line with the LW equation, although at a slower rate than in, for example, glass capillaries [29]. The controlled wicking of fluid in soft materials, such as gels, is of great importance as such systems are used in microfluidic applications for diagnostics [30,31]. Silva et al. reported a stick–slip motion occurring in glass capillaries coated with a dried hydrogel [32]: as the meniscus advanced, it became successively pinned and unpinned due to swelling and local deformation, indicating that substrate deformation significantly affects the contact-line dynamics of the liquid movement. From a broader perspective, not only gels are soft, but also often foams and various types of paper, comprising a vast range of materials and applications. Gel applications have some advantages over lab-on-a-paper applications, such as transparency, non-toxicity, and biocompatibility with cells. Despite their relatively short shelf life, polysaccharides are a cheap, renewable, and readily available material. Fluid wicking in soft hydrophilic materials of various geometric shapes has been much less studied than wicking in hard channels.

Here we report on wicking speed within geometrically structured soft materials obtained using 3D-printed moulds in which a hydrogel (i.e., calcium alginate) was allowed to cure. This method results in channels with rectangular cross-sections and open top sides. We can control the wicking speed of an imbibing fluid in a main channel by varying the tilting angle and position of side channels. The width of the side channels are varied to investigate if small or large pores are filled first. The use of 3D-printed moulds in combination with curable hydrogels opens up the possibility of the rapid, cheap, and simple use of variously structured materials in which the controlled wicking of fluid is obtained.

2. Method and materials

2.1. Drawing of a 3D mould

An overview of the process of fabricating microchannels (μ-channels) in gels is shown in Fig. 1. A mould was drawn in 3D using AutoCAD (Version 2014; Autodesk, San Rafael, CA, USA). Reservoirs for depositing the liquid were designed to hold sufficient liquid volume to fill at least the entire channel.

The mould was designed with side channels added on one or two sides of a main flow channel with varying tilting angles and widths (see Fig. 2). The sketch shows a top view of part of a channel. As the junctions, we define the point in the main channel where the side channels are connected to the main channel. The