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Experimental characterization of the effects of geometric parameters on evaporative pumping

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ABSTRACT

This study is interested in determining the experimental relation between the suction pressure and evaporation rate from the upper surface of a flat, thin porous membrane, which naturally draws water from a reservoir, and its microchannel feeding system. The effects of three main design parameters of a water delivery system on the evaporation rate of the membrane are considered: (i) the diameter of the microchannels irrigating the membrane, (ii) the length of the irrigating microchannels, and (iii) the surface area of the membrane. Additionally, we also evaluated the effect of the pumping height (i.e., the vertical distance between the membrane and the main reservoir) on the evaporation rates for the three design parameters. While the maximum evaporation rate from the membrane is a function of the membrane's properties (e.g., permeability and porosity), as well as the ambient conditions (e.g., temperature, pressure and humidity), this study focused on determining the geometric parameters of closed water-feeding microchannels that properly hydrate a porous membrane while not impeding evaporation. Results indicated that the evaporation rate was mostly unaffected by the channel dimensions considered. Moreover, evaporation rates increased with increasing surface area (between 20.3 cm^2 and 176.7 cm^2) but at a decreasing rate of return. Finally, the suction pressures achieved were inversely related to hydrodynamic pressure drop and were unaffected by the membrane diameter.

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1. Introduction

The ability to move small, accurate amounts of fluid, less than 1 ml per minute, has become increasingly in demand in a wide range of fields from medicine to electronics. In biological applications, precise dosing is required for medicine delivery [1]. In chemistry, species separation is desired for mass spectrometer analysis [2]. With the continual shrinking of electronics, small amounts of liquid are used in microelectronics cooling [3–5]. The applications go on and on for pumping small amounts of fluid including circulation, metering, and point to point transfer. Until recently, the prevailing method has been to use micropumps.

Micropumps have been offered in both a valve and valveless configuration [6]. For the most part, valve micropumps rely on electromechanic devices that utilize an oscillating motion to displace fluid, e.g. electromagnetic [7], electrostatic [8], piezoelectric [9], and thermopneumatic [10] actuation. However, the oscillation often produces pulsating streams, which can be undesirable for certain applications. Valveless micropumps provide continuous flow by directly imparting energy to the fluid. Many techniques have been developed in this area including electrochemical [11], electrohydro-dynamic [12], electrokinetic [13], electroosmotic [14], and magneto-hydrodynamic [15]. One of the main drawbacks of valveless pumps, however, is related to substantial power requirements [6].

In light of the limitations mentioned, a new branch has emerged in pump research based on transpiration. Transpiration is the continuous, passive flow of water in plants from the soil to the atmosphere. In plants, whose height is greater than the capability of capillary action to overcome gravity, transpiration is relied on for moving water and minerals throughout the body via xylem [16]. Additionally, transpiration prevents leaves from overheating in direct sunlight [17,18]. One of the main advantages of transpiration is that it is a passive evaporative pumping operation that does not require the assistance of pumps, valves or moving parts, making it a robust system with diminished maintenance requirements. Furthermore, the process is noiseless and does not cause vibrations, which could be extremely important in certain applications.

According to Dixon and Joly's Cohesion Theory, suction pressures up to −1.0 MPa can be imposed by root systems, pulling water from the soil to replenish what was evaporated from the leaves [19–21]; a good example being the redwood trees of the Pacific Northwest, which can be over 100 m high [22]. While more extensive investigations have shown that transpiration is actually more complicated and utilizes additional processes (e.g. evapora-

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tion, osmosis, wicking and others) than Cohesion Theory first proposed [23], Cohesion Theory is a good basis for this preliminary investigation.

Previous work has been done to mimic transpiration in plants. For example, Wheeler and Stroock [21] constructed a synthetic tree structure that used evaporation from a membrane to pull water through a microfluidic channel. Results indicated flow rates of 2.3 nl/s, representing a calculated pressure drop of 10 kPa. Borno et al. [24] also used microfabrication to build an evaporation driven synthetic leaf reaching measured flow velocities up to 1.5 cm/s. Moreover, several groups have used evaporation from porous media as a passive means to move liquid through microfluidic channels for biomedical applications [25–27]. In Guan et al. [25] setup, the experimental evaporative micropump provided a consistent flow rate of 46 nl/s for vertical displacements up to 2 m. In a later study, the same group investigated the effects of ambient relative humidity, temperature, and evaporative surface area on flow rate provided by the micropump [26]. Li et al. [27] designed an evaporative micropump consisting of plant stomata-shaped evaporation apertures. Lynn and Dandy [28] used evaporation from a meniscus to drive flow through a microchannel network. In doing so, they were able to maintain a constant flow rate for a period of time exceeding 1 h.

In this study, we designed, constructed, and tested a low-tech evaporative pumping system that does not require microfabrication. The system was designed such that we could mimic a leaf's evaporative surface, since this can be considered a two-dimensional ramifying structure [16]. The "xylem" of the microfluidic system was a combination of polyetheretherketone (PEEK) microchannels and Tygon tubing for larger passageways. The evaporative surface was a thin porous membrane (Fisherbrand Glass Fiber Filter Circles, G6). Three parameters were investigated: (i) the diameter of the channel feeding the membrane, (ii) the length of the microchannel, and (iii) surface area of the evaporative surface. Additionally, the suction pressure of evaporation was measured and related to pumping height of the system (i.e., the height difference between the evaporating surface and the supply reservoir). The aforementioned parameters have been parametrically investigated to determine when each limits the self-driven evaporation process.

2. Materials and methods

2.1. Experimental setup

The evaporative pumping system consisted of a porous membrane connected to a distilled water reservoir via a microchannel and tubing, as shown in Fig. 1. The reservoir sat on a balance (Denver Instruments PI – 214, range 0–210 g, resolution 0.1 mg) which recorded mass loss to a spreadsheet file using Denver Instruments' proprietary software. To prevent unwanted evaporative losses from the reservoir to the atmosphere, its top was covered with a lid while a 2 mm diameter pinhole maintained the reservoir pressure equal to the room pressure. Due to the slow rate of mass decrease in the reservoir, it was assumed that the interior of the reservoir was at the same pressure as the air in the room. Because all mass loss from the water reservoir was due to evaporation from the porous membrane, the balance was effectively recording the evaporation rate from the membrane. Due to the balance's sensitivity to air currents, this was placed in a specially designed acrylic isolation box so the balance sliding door could remain open during testing. Additionally, the mass loss from the covered reservoir by itself was confirmed to be negligible when the balance was left to record mass while no membrane evaporation was occurring. The mass rate decrease was found to be less than 1% of the lowest evaporation rate that would be tested as a result of the experimental setup configurations.

The microchannels used to irrigate the membrane were high-pressure polyetheretherketone (PEEK) tubing, which fit snuggly into a small perpendicular hole in the center of an acrylic plate surface that served as support for the membrane. Sealant was applied to the underside of the acrylic where the tube entered to prevent leakage. Three values of channel diameter, length, and membrane area could be interchanged: (i) diameters of 127, 177.8, and 254 μm, (ii) lengths of 2.54, 7.62, and 15.24 cm, and (iii) areas of 20.3, 81.1 and 176.7 cm^2 (before wetting). Additional tubing, 1/8th inch ID Tygon tubing, was used to connect the microchannel to the reservoir – a color scheme[1] was used in Fig. 1 in order to identify the PEEK channels and the Tygon tubing, red and grey tubing, respectively. All tubing was purged of air bubbles to ensure single phase flow. The system also featured Swagelok valves for turning the system on and off – the operation procedure will be discussed later. A parallel study showed that any pressure drop in the Tygon tubing and connectors was negligible compared to the pressure drop in the microchannel and did not affect the system. Additionally, the Tygon tubing produced negligible capillary rise of the fluid.

Two additional lines were teed off from the main supply line. One line connected to a ±34.475 kPa differential pressure sensor (Omega PX26-005DV, calibrated uncertainty was 0.017 kPa at 95% confidence) with one side open to atmosphere. Pressure was calculated using the density of water at atmospheric pressure and a temperature of 23.5 °C. The other line connected to another reservoir placed high above the channel. The purpose of this second reservoir was for initially wetting the membrane to start the system. It too featured an on/off valve.

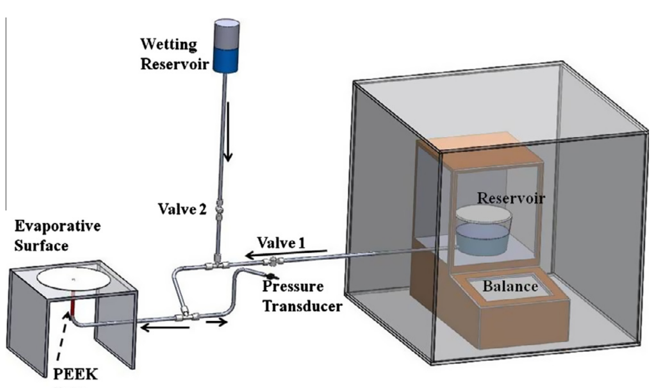

Fig. 1. Experimental evaporative pumping system setup.

2.2. Membrane characterization

The evaporative surface was a thin porous membrane (Fisherbrand Glass Fiber Filter Circles G6). The microstructure was examined using a Jeol JSM-5610 scanning electron microscope (SEM). The structure was of a random nature with much interlocking between fibers as shown in Fig. 2a–c. The fibers were relatively smooth, constant diameter rods ranging in diameter up to ~3 μm; however, the fiber length could not be identified. Spacing between fibers was estimated to be up to 7 μm. The size of the fibers and spacing between fibers plays a major role in the capillary spreading of a fluid in the membrane.

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

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