A POWERLESS VALVING SYSTEM FOR FLUID FLOW IN PAPER NETWORKS

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ABSTRACT

This paper presents a powerless valving system for fluid flow in two-dimensional paper networks (2DPN) using swellable polymer actuators. The valving system is based on solvent-triggered expansion of strategically-located expanding polymer actuators; both physically disconnected paper channels that become connected (on-switch) and connected paper channels that become disconnected (off-switch) were developed. , On- and off-switches were combined and simultaneously activated by the expansion of a single actuator, effecting diversion of flow from one channel of the network to another. This valving system enhances the utility of the 2DPN technology, enabling the performance of many autonomous integrated chemical processes.

KEYWORDS

Paper microfluidics, 2DPN, porous membranes, wicking flow, point-of-care diagnostics, valves

INTRODUCTION

2DPNs provide a promising alternative to conventional microfluidic systems for handling microliter volumes of fluids, owing to their low cost and the absence of need for external pumps [1, 2]. Paper-based devices have found important applications in the detection of analytes from biological samples, especially in the developing world and other remote and low-resource settings [3, 4]. They have also been used for environmental monitoring [5] and food quality control [6] applications. In comparison with conventional microfluidic devices, however, 2DPNs currently lack advanced fluidic control tools. Some efforts have been made to incorporate functional elements in 2DPNs to direct flow of fluid along desired paths. Li *et al.* have demonstrated filters and manually operable switches [7] in paper. Martinez *et al.* developed devices that could be programmed by an operator to set fluid flow paths [8]. We also demonstrated manual activation of path switching in a low-cost, point-of-care viscous sample preparation device for molecular diagnosis in the developing world; an example of microfluidic origami [9]. In this paper, we advance the field by developing valves that can be programmed to turn fluid flow through 2DPNs on or off, as well as divert flow from one channel of the network to another. This valving system provides new capabilities to 2DPNs and enables multi-step and precisely-timed fluidic operations to be performed in 2DPNs.

MATERIALS AND METHODS

Devices were fabricated by stacking multiple layers of 10 mil thick Mylar sheets backed with adhesive on one side (*Fralock*, Valencia, CA). Plastic-backed nitrocellulose FF85 (*GE Healthcare*, Piscataway, NJ) was used as the porous substrate for fluid flow. A 2% w/v gel of sodium polyacrylate, a super-absorbing polymer, was prepared in deionized (DI) water and used as an expanding element for valve actuation. Glass fiber strips of GR8975 (*Ahlstrom*, Helsinki, Finland) were used to deliver DI water to the expanding polymer during valve operation. All designs were drawn using the CAD program DraftSight (*Dassault Systemes HQ*, France) and parts were cut using a CO_2 laser cutter (*Universal Laser Systems*, Scottsdale, AZ). A system for creating bands of colored fluid previously developed in our lab [10] was used for tracking flow through nitrocellulose. Images of flow through nitrocellulose strips were acquired at intervals of 5 seconds using a Logitech Pro 9000 (*Logitech*, Newark, CA) webcam operated through HandyAvi (*AZcendant®*, Tempe, AZ) software.

RESULTS

An “on-switch” was developed by placing two nitrocellulose strips, A and B, on separate horizontal planes (Fig. 1A) so that there was no contact between them. Fluid introduced into strip A does not flow into strip B during this time (off position; Fig. 1B). The valve was held in this off position for 28 minutes (Fig. 1B). The valve was actuated by flowing deionized (DI) water through the glass fiber strip into the actuator (Fig 1.B). Expansion of the actuator raised one end of strip A, established its contact with strip B, and caused fluid in strip A to flow into strip B, thereby turning on the flow switch (Fig. 1A,B). The average response time, defined as the time required for the yellow fluid front to traverse a certain distance along strip B (up to red arrow; Fig. 1B) after DI water delivered through the glass fiber strip reached the actuator of the on-switch was 4.7 minutes with a coefficient of variation of 15.7% (N=5). Next, an “off-switch” was developed by placing two nitrocellulose strips on a single plane with one end overlapping, such that fluid introduced into strip A flowed into strip B initially (on position, Fig. 2A,B). The valve was held in the on position for 10 minutes. On actuation of the valve, one end of strip B was lifted off the plane and disconnected from strip A (Fig. 2A). Thus, actuation of the valve stopped the flow of fluid through the strips (Fig. 2A,B) as shown by the plot of fluid velocity as a function of time (Fig. 2C). Finally, the on- and off-switches were combined to make a “flow diversion” switch to route the flow of fluid from one channel of the network to another. A third strip, C, was introduced into the "on-switch" setup (Fig. 1) and placed in contact with strip A (Fig. 3A). Yellow fluid introduced into strip A initially flowed into strip C, placed perpendicular to strip A (Fig. 3B). After 20 minutes, the valve was actuated by introducing DI water into the glass fiber strip. On actuation, strip A disconnected from strip C and established contact with strip B (Fig. 3A). Thus, flow introduced into strip A was effectively diverted from strip C to strip B (Fig. 3B).

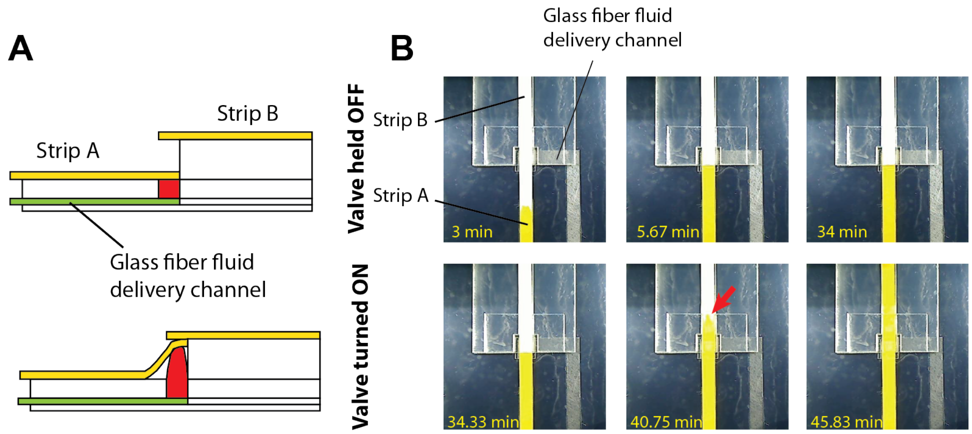

Figure 1. ON Switch. A*: Schematic of switch function;* ***B****: Time lapse images of working switch. The average response time of the on-switch was 4.7 minutes with a coefficient of variation of 15.7% (N=5).*

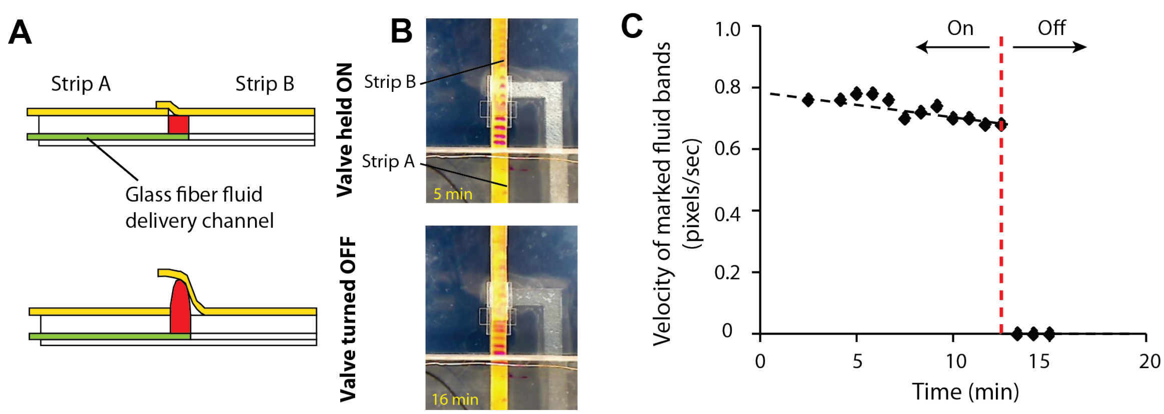

Figure 2. OFF Switch. A*: Schematic of switch function;* ***B****: Images of the switch held in the on and off state;* ***C****: Plot of velocities of fluid bands as a function of time, before and after activating the off-switch.*

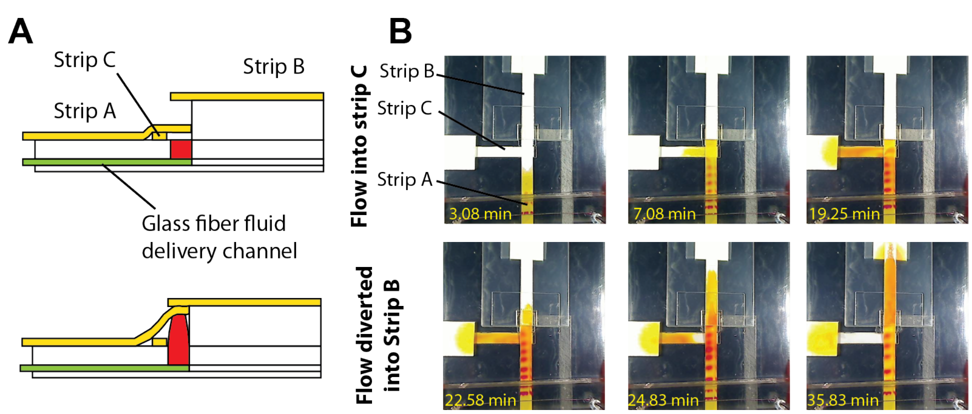

Figure 3. Flow diversion switch. A*: Schematic of switch function;* ***B****: Time lapse images of working diversion switch.*

Serpentine glass fiber strips were introduced into the devices to automate valve activation. In all previous demonstrations, an additional user step of adding DI water to the glass fiber strip was necessary for activating the valves. Introducing a long serpentine glass fiber strip produced a delay in the delivery of DI water to the actuator, allowing simultaneous introduction of all fluids into the device. An on-switch incorporating such a serpentine glass fiber strip was constructed (Fig. 4A). Yellow fluid and DI water were simultaneously introduced into nitrocellulose strip A and the glass fiber strip, respectively. The yellow fluid front reached the end of strip A at approximately 5 minutes and did not advance beyond that because the valve was in the off position (Fig. 4A). The valve remained off for approximately 4.5 minutes. At 9.75 minutes, DI water from the glass fiber strip reached the activator and turned the valve on, allowing flow of the yellow fluid into strip B (Fig. 4A). The duration for which the valve is held in the off position depends on the length of the serpentine glass fiber strip used. The time required for DI water to flow through different lengths of glass fiber strips was measured (N=5 for each length) and is shown in Fig. 4B.

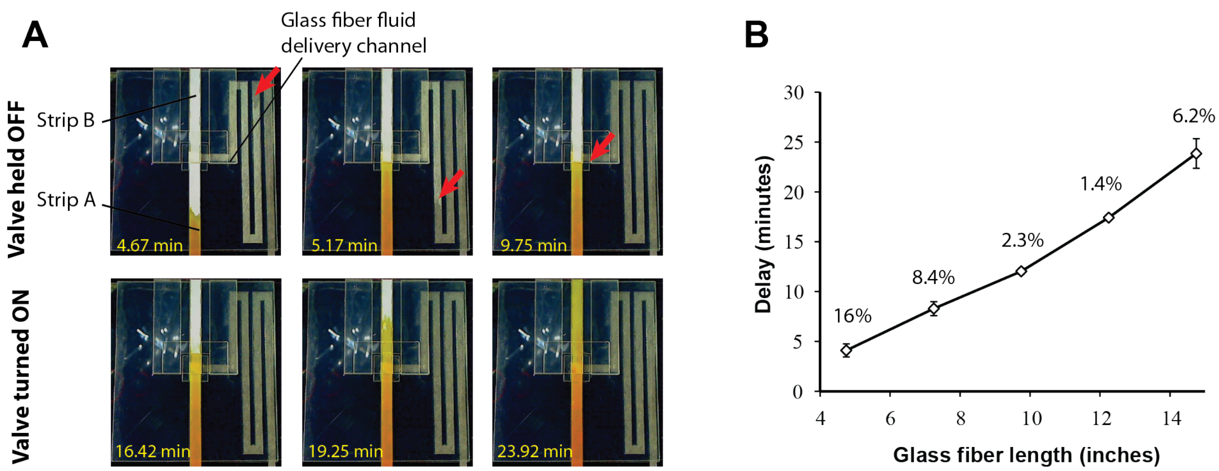

Figure 4. Automatic switch activation. ***A***: *Time lapse images of the operation of an "on switch" with a serpentine glass fiber strip for fluid delivery to the actuator. Red arrows indicate the location of DI water front.* ***B***: *Time required for DI water to traverse different lengths of glass fiber strips. Error bars are standard deviations and numbers indicate coefficients of variation.*

CONCLUSION

Valves based on expanding polymers can be effectively used to turn fluid flow through paper networks on or off or divert fluid flow from one channel of the network to another. The activation of these switches can be precisely timed by designing fluid delivery channels that provide the appropriate flow delay.

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