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Short communication

Rapid prototyping of pneumatically actuated hydrocarbon gel valves for centrifugal microfluidic devices

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ABSTRACT

A novel, easy to prototype hydrocarbon gel-based active valve was developed for use in centrifugal microfluidic devices. The valve has been demonstrated to restrict flow by an additional 1000 revolutions per minute (RPM) when compared to a passive capillary valve of the same size located at the same radius. Opening of the valve is accomplished in a contactless manner using a stream of focused compressed air. The ease of fabrication, low cost and small dimensions of the gel valve offer the potential for integration of multiple valves of this type into multi-process centrifugal microfluidic systems.

1. Introduction

Microfluidics allows the miniaturization of multiple analytical processes into a single micro total analysis system (μTAS). The small dimensions and potential portability of these systems render them attractive for in-situ chemical analysis and point of care diagnostics [1].

Centrifugal microfluidic (CM) devices incorporate the portability, efficiency and other benefits of traditional microfluidic systems with the consistent and tuneable flow control associated with centrifugal force [2–5]. In these devices, which often take the form of compact discs (CD), centrifugal force induced by rotation of the device initiates liquid flow, eliminating the need for external pumps and their connections. The radially uniform nature of centrifugal force allows simultaneous analysis on parallel units rendering CM conducive to high throughput analysis [2,4].

The creation of fully integrated systems incorporating multiple processes often requires precise flow control to ensure completion of each sequential unit operation. On CM devices, this requirement can be most often met by passive and active valves.

Passive valves, such as capillary, hydrophobic, Coriolis and siphon-based valves exercise flow control using processes correlated to the device's rotational frequency [2,3,5–8]. Capillary valves gate liquid flow by pinning the meniscus of the advancing liquid at the interface between the valve and a channel or chamber of much larger cross section until sufficient pressure is generated through centrifugal force for the liquid to flow (or “burst”). The wetting properties of the liquid, and the geometry of the channel, such as its cross section and head height, determine the frequency required to induce flow, known as the burst frequency [2,3]

The implementation of multiple sequential operations using capillary burst valves requires each valve to be more restrictive than the previous valve. Generally speaking, the smaller the valve, the higher the burst frequency. However, as the radial position (from the center) of a given size valve is increased, a lower burst frequency is observed as the centrifugal force increases with the radial position. The combination of these factors limits the number of sequential operations possible using passive capillary valves. Despite their prevalence, passive capillary valves can present irreproducible burst frequencies, and their integration into a rapid prototyping process is often time-consuming and labor-intensive [6]. Hydrophobic valves suffer from similar drawbacks as they rely on a related principle [2]. Coriolis valves provide an efficient method of flow switching; however they require high angular velocities to successfully switch the flow, limiting their compatibility with sequential operations. Siphon-based valves have been developed to control liquid flow through an integrated siphon. These valves often require surface treatment of the siphon channel, which complicates their fabrication and often limits their lifetime. In addition, the device must be stopped to prime the siphon, leading to the possibility of unintended liquid flow in other parts of the device due to capillary action in the absence of centrifugal force.

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Active valves rely on a frequency independent process such as physically blocking a channel to restrict flow, allowing for more precise flow control and greater flexibility in design [7,8]. Currently, there are fewer and less diverse options for active valves when compared to their passive counterparts. Phase change-based valves represent the majority of presently available active valves. Active valves incorporating hydrogel, ice, wax and magnetic nanoparticle embedded wax have been demonstrated for use in microfluidic devices [9–11]. Amasia et al. [11] developed an ice plug for CM devices for use with PCR. However, it was necessary to stop the disc to open the valve, which is undesirable in many applications. Integration of multiple valves of this type requires a thermoelectric module for each valve position and the modules must be properly distanced to avoid the opening of neighboring valves, thereby limiting the number of valves that can be incorporated into a single device. In contrast, the paraffin wax-based method of Abi-Samra et al. [8] irradiates the entire disc and offers selective valve opening based on the difference in melting points of wax plugs with varying composition. However, this irradiation may be unsuitable for use with biological samples. In addition, the different wax compositions required for each valve complicate large-scale valve integration. The Laser Irradiated Ferrowax Microvalves (LIFM) developed by Park et al. [7] utilize iron-oxide nanoparticles incorporated in a ferrowax hydrocarbon mixture that is melted by a low intensity laser. This method allows sequential valve opening by focusing the laser beam on the radius pertaining to the wax plug to be opened. While LIFMs offer a fast and selective sequential valve solution, the required materials are expensive and need complex preparation and equipment, such as a moveable laser.

To facilitate the integration of multiple sequential operations on CM devices, an inexpensive, non-radiative, active valve with a simple fabrication process is desirable. We have previously developed a non-contact pneumatic pumping technique that can be utilized to enhance and expand the capabilities of CM devices [12,13]. In this paper, we extend the pneumatic method with a new active valve technique that uses an inexpensive, externally controlled hydrocarbon gel valve opened by a jet of compressed air.

2. Material and methods

2.1. Device design and fabrication

Fig. 1 presents the design of the CM device used to demonstrate the valve's effectiveness. The hydrocarbon gel utilized in the device is a commercially available petroleum jelly. The pneumatic micro-valve comprises a hydrocarbon gel plug (Fig. 1e and g) located inside an 800 μm deep channel (Fig. 1d) and positioned to block flow out of a 100 μm deep channel (Fig. 1c) connected to an 800 μm deep liquid reservoir (Fig. 1e). The plug is slightly thicker than the channel from which liquid flows while only partially covering the channel in which it resides. This allows easy displacement of the plug through air pressure applied at an inlet directly above the valve (Fig. 1d), forcing the plug to disperse in the radially outward direction. An air vent connected to the reservoir facilitates injection (Fig. 1a).

The device was constructed with the rapid prototyping method described by Kido et al. [14]. The five layers of the device (Fig. 2) were designed using the SolidWorks computer-aided-design software (SolidWorks Corp., Concord, MA, USA). Each disc layer (Fig. 2a, c and e) consisted of a 600 μm polycarbonate DVD machined using a four-axis CNC mill (MDX-40A, Roland Corp., Los Angeles, CA, USA). The disc layers were bonded together using 100 μm double-sided adhesive layers (Fig. 2b and d) (FLEXmount DFM-200-Clear V-95 150 poly V-95 400, FLEXCon, Spencer, MA, USA) with the corresponding channels and chambers cut by xurography using a cutting plotter (CE3000Mk2-60, Graphtec America Inc., Santa Ana, CA, USA).

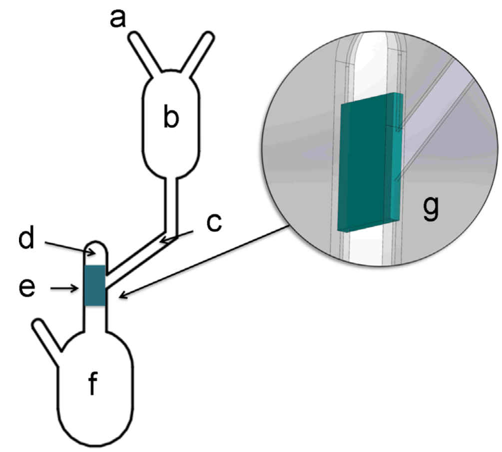

Fig. 1. Demonstration unit: Design of a single unit of the CM device. Each device contains six units with (a) injection and vent ports, (b) liquid reservoir, (c) 100 μm deep channel cut in the bottom adhesive layer, (d) 800 μm deep channel with air inlet at top, (e) petroleum jelly plug, (f) receiving chamber, and (g) expanded view of junction of plug highlighting the critical difference in channel depth and plug height.

A partially assembled disc was constructed from the base disc and bottom adhesive layer (Fig. 2a and b). Keeping the protective peel on the adhesive, a dot of commercial petroleum jelly was placed in the 800 μm vertical channel blocking the 100 μm diagonal channel (Fig. 1c). A thin piece of flexible plastic was used to level the surface of the plug with the top protective layer on the adhesive. After peeling off the protective layer, the ~4 mm long plug projected slightly above the plane of the 100 μm channel. The remaining layers were then assembled with each layer being sealed to the previous with a hand roller. The final device was not cold-laminated to avoid the irreproducible displacement of the gel plug due to the added pressure.

Although the disc is designed with multiple air inlets on the same radius for rapid and consecutive opening of parallel valves, all inlets except the one being tested were covered using tape to allow the testing of one valve at a time without compromising the integrity of the surrounding valves.

2.2. Experimental setup

A centrifugal experimental setup previously described by Duford et al. [15] was utilized to evaluate the pneumatic valve device. This setup was augmented with a color digital camera (GRAS-14S5C-C, Point Grey, Richmond, BC, Canada) positioned at 90° to the disc surface to allow acquisition of in-motion images. The pneumatic system utilized for valve actuation was derived from the setup described by Kong and Salin [16] with modification to the air outlet. A microcapillary pipette tip (200 μL, Denville Canada, Toronto, ON, Canada) was attached to the tubing to focus the air stream on the disc. The nozzle was positioned 5 mm above the disc to maintain a non-contact configuration. The radial position of the air nozzle was controlled via a linear actuator and set to 39 mm from the disc center so that the nozzle aligned with the air inlet (Fig. 1d). The components of the experimental setup and pneumatic system were synchronized via software (LabVIEW, 8.6, National Instruments, Vaudreuil Dorion, QC, Canada). Experimental settings such as the radial position of the air nozzle, air triggering, rotational frequency and data acquisition parameters were pre-set by the user into the LabView program.