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Gating valve on spinning microfluidic platforms: A flow switch/control concept

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ABSTRACT

Flow switching on spinning microfluidic platforms, i.e., usually based on Coriolis force enables more sophisticated and flexible assay sequences such as mixing, metering, preparation and manipulation of high quality DNA and so on. Thus far flow switching techniques on centrifugal microfluidic platforms have been accomplished by changing the spinning direction or by exploiting external power sources, e.g., pneumatic or thermo pneumatic pressure. We have devised a gating microstructure that controls the flow direction in centrifugal microfluidics without the need of changing the direction of the disc rotation, applying surface treatments or employing external sources. The device is a frequency dependent valve that is able to direct the flow to one direction (e.g., cw) at low frequency and to the opposite direction (e.g., ccw) at higher frequencies. At low frequencies the liquid follows a micropath as a consequence of the specific gating microstructure and at higher frequencies liquid follows the direction of the Coriolis force. The flow behavior of the new valve for di water as well as liquids with different physicochemical properties has been investigated experimentally and numerically. The results show that the new valve is able to control the flow direction on spinning microfluidic platforms for liquids of the wide range of physicochemical properties.

1. Introduction

Centrifugal microfluidics, also called lab-on-a-disc, is an attractive option for various biomedical and chemical applications such as blood plasma separation, disease screening, and drug testing, cellular, etc. [1–9]. They use centrifugal force to propel and manipulate fluids in order to automate conventional clinical diagnostic analyses such as Enzyme-Linked Immunosorbent Assays (ELISAs). The series of sequential diagnostic analyses steps typically performed by skillful technicians are miniaturized and implemented on spinning microfluidic platforms to achieve more accurate results of the bioassays by elimination of possible human involved errors [10,11]. To date, many complex microfluidic operations have been demonstrated on a single disc towards development of integrated sample-to-answer systems or micro total analysis systems (μTAS) [2,10,12,13].

The spinning disc consists of a network of micro channels, micro valves and reservoirs. Micro valves are the critical part of a centrifugal microfluidics and are mainly used for flow control and manipulation. There are passive valves and active valves; the former only needs a change in rotation frequency (rpm) to be activated but the latter require an additional force or a source other than centrifugal force, e.g., the use of heat to melt paraffin wax plugs [10]. Passive valves are popular for the use in CD-like microfluidic platforms and can be further classified into non mechanical valves (e.g., capillary valves); and mechanical valves (e.g., microballoon valve and dissolvable films) [10,14–18]. Capillary passive valve are often designed by making a sudden expansion in hydrophilic channels or sudden constriction in hydrophobic channels [19,20]. Capillary valves retain liquid at the expansion/constriction point in the channel until the pressure induced by the disc rotation is sufficient to overcome the pressure barrier at the capillary valve. The rotational frequency at which the hydrostatic pressure in the capillary overcomes the capillary pressure is called the burst frequency of the capillary valve. The burst frequency of the capillary valves is dependent on the contact angle between the liquid and the

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channel wall, the angle of expansion/constriction, the conduits size and their positions on the CD [10,14,21,22]. These parameters have been extensively studied over the last decade [14,19,21,23,24].

Flow in centrifugal microfluidics is intrinsically unidirectional issuing from the disc center toward its edge, while at T-junctions it is directed by the Coriolis force. The ability to employ multi-directional flow on CD allows for better use of discs' real estate and increases flexibility of fluidic operations. To date, several passive and active techniques have been introduced in order to develop multidirectional flow on the centrifugal microfluidics such as siphoning, thermo pneumatic pumping and "centrifugo-dynamic inward pumping [10,25,26]. The most recent passive technique to pump liquid against centrifugal pressure is employing latex microballoon embedded in the centrifugal microfluidic platforms [16]. Routing of liquids is necessary for complex operational sequences (that include sample preparation such as fractionation and DNA extraction, reagent mixing, volume definition, etc.) on the centrifugal microfluidics platforms [27–32]. The control of fluid routing can lead to development of multiplexed ELISA assay on centrifugal fluidics platforms [27]. In addition to the fluid routing (fluid switching) that relies on Coriolis force [33], it can also be performed via an air pocket trapped between two fluids [31]. These flow switching techniques could not be easily applied for development of clinical assays on CDs (or it requires a complicated design) as the abrupt change in the direction of rotation (necessary for these flow switching techniques) may disturb other operations on the disc (e.g., unwanted activation of siphoning and so on). An active flow switch method employing a periodic air supply in order to change the flow direction has been proposed by Kong et al. [28]. Although this method is able to change the flow without changing the spinning direction of the disc, possibility of contamination is also increase, making it less desirable for clinical applications. Recently, Lin [27] has introduced a passive splitter structure that evenly distributes the liquid at the T-junctions when it is required in the centrifugal ELISA chips. Given limitations of the existing flow switching solutions, and due to the diversity of clinical and chemical assays there is a clear need for development of the new valving techniques. For instance in many clinical assays siphon valves are necessary during blood purification at high speeds, while in assays with many regents that need long term storage barrier waxes or films based valves are effective. This paper introduces a novel concept called gate valve (GV) to control the liquid flow on centrifugal microfluidic platforms at T-junctions that would not require external actuation sources or rely on change in the spinning direction. The valve allows gating the liquid against Coriolis force direction as a consequence of a specific geometrical structure of the valve. The valving mechanism is experimental and numerically tested for liquids with various chemical and mechanical properties. The volume of fluid (VOF) method within the commercial code of ANSYS-Fluent software is used to simulate the valve behavior. The numerical results are validated with our experimental investigations and an existing theoretical model. Finally we demonstrate a switching application without the use of external power sources, surface treatments and changing the spinning direction.

2. Materials and methods

2.1. Liquid gating

Unlike Coriolis force the geometrical structure of microvalve has not been reported as a method to control the flow direction on spinning microfluidic platforms. Here a new concept of gating valves is demonstrated that exploits special geometrical structures of the valve at T-shape junctions. A GV is a flow control means that exploits both geometrical effect and Coriolis force

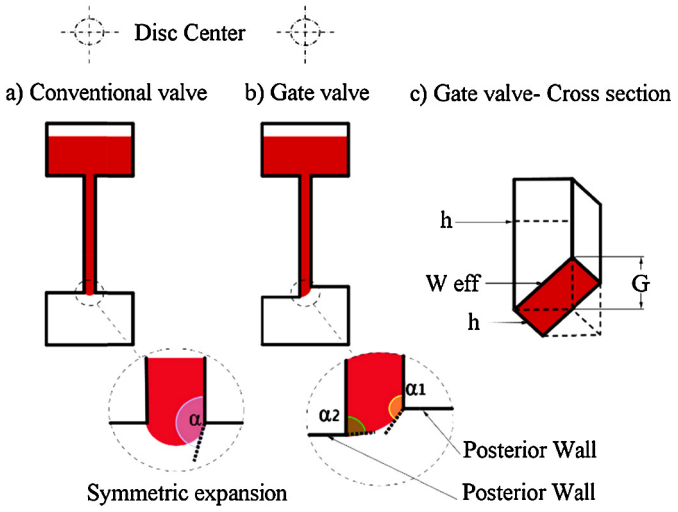

Fig. 1. A sketch of (a) a conventional capillary valve (b) a Gating valve and (c) isometric view of GV.

simultaneously to determine flow direction on a spinning platform. At low rotational frequencies the liquid flow is gated into the opposite direction of the Coriolis force while it flows in direction of the Coriolis force at higher frequencies. Fig. 1 compares the geometrical structure of a GV (Fig. 1b) and a conventional valve (Fig. 1a) at T-shape junctions. As compared to a conventional valve GV allows controlling the interaction between the capillary force and the centrifugal force at the fluid/gas interface. GV is fabricated by creating an asymmetrical outlet chamber which produces an offset between the posterior and anterior expansion walls as presented in Fig. 1b and c. The GV mechanism is investigated by studying the effect of gating parameter G on flow behavior. The capability of the valve to stop and control the flow direction and the effect of G on burst frequency of the valves are discussed in the Results section below.

2.2. Experimental set up

The CD-like microfluidics with the new valve design was fabricated using a Computer Numerical Control (CNC) machine (model VISION 2525, by Vision Engraving and Routing Systems, USA). The micro structures were milled on a 4 mm thick Polymethyl methacrylate (PMMA) layer. To create a microfluidic disc, this plastic layer is bonded by Pressure Sensitive Adhesive (PSA) layer (by FLEXcon, USA) to another 2 mm thick PMMA layer that contains venting holes. A cutter plotter (model PUMA II, by GCC, Taiwan) is used to cut the CD-like microfluidic design in the PSA layers corresponding to the design of the PMMA layer. A custom-made system consisting of a digital disc spin test system, laser sensor and a high speed camera is used to perform the experiments.

2.3. Characterization

The flow switch was experimentally tested by fabricating a number of GVs with G varying from 10 μm to 300 μm by a step increase of 10 μm. In order to enhance the visual observation of the flow direction, the outlet chamber was divided by a V-shape wall as shown in Fig. 2. The figure shows CD-like microfluidic containing both the conventional and GVs with the capillary width and height of 400 μm and 250 μm, respectively. Fig. 2 shows a step by step experiment conducted to characterize the valve by comparing liquid motion in a conventional (Fig. 2a–d) valve and in a GV (Fig. 2e–f). The source chambers of the conventional and gated microfluidic systems are primary loaded with the blue and red dyed di waters, respectively. Thereafter the platform is spun