DEFORMABLE-CHANNEL CLOSED-LOOP MICROFLUIDIC PLATFORM FOR CONTINUOUS AND CONSTANT-PRESSURE FLUID CIRCULATION

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ABSTRACT

Maintaining constant pressure is a critical characteristic in many analysis processes. This paper reports a new type of closed-loop micro circulation platform that produces continuous, constant-pressure fluidic circulation, which can be applied to various analytical instruments. The platform contains a circular closed-loop channel that can be deformed by electromagnetic-hydraulic micropumps, thus maintaining, a constant volume and constant pressure of a fluid during circulation. Successful demonstration has been performed to show continuous complete fluid circulation, and it has achieved suppressing pressure-fluctuation by 80% below ±2 Torr through the circulatory closed-loop channel (69×4×0.6mm).

KEYWORDS : Constant pressure, Constant volume, Circulatory platform, Closed-loop

INTRODUCTION

Most material separation methods in the field of analytical chemistry, such as liquid chromatography (LC), require stable constant pressure fluidic flow for accurate analysis [1, 2]. Conventionally, generating fluidic flow through micro channels (analytical column) in microfluidic LC instruments have been achieved by directly inserting a micropump within the process loop. In such an LC system, mechanical micropumps are utilized to ensure a larger pumping quantity, and lower induced electric charge on surrounding components (Table 1). However the use of mechanical micropumps results in significant pressure fluctuation and irregular flow rates (Fig.1). Such drawbacks are mainly caused by the volumetric expansion and contraction during transient membrane movement [3, 4].

We report a novel closed-loop micro circulation platform that avoids any transient volume variation in the fluidic loop by constantly maintaining the membrane deformation at the same volume. Such a configuration, thus, encloses and translates a fluid within the constant volume between deformable membranes and minimizes the pressure fluctuation.

STRUCTURE AND OPERATION PRINCIPLE

The structure of this platform consists of three functional layers: hydraulic actuators, actuation membranes, and circulatory channel layers (Fig. 2). The hydraulic actuator layer provides the paths for the movement of the hydraulic fluid for the membrane deformation. The designed path allows the membrane deformation to propagate into one direction, and the movement is driven by a high-force electromagnetic-hydraulic micropump, previously reported [5]. The actuation membrane layer is fabricated of a thin and flexible polymer and rotates the fluid as gradually inflated by the hydraulic fluid. The circulatory channel layer serves as the analytical channel where the target objects can be rotated. The cross-section, (type A: A2-A2') and (type B: B1-B1'), of the channel are semi-circular (the diameter 0.6mm) (Fig. 2). Onto the channel layer both inlet and outlet connectors are attached. Note that the circulatory channel deforms without conventional valves. This platform has two distinct types: type A (70×14×7.5mm) is constructed with straight channel and type B (69×4×0.6mm) is constructed with curved channel which is semi-circle shape (Fig. 2).

Table 1: Characteristic comparison among mechanical, non-mechanical, and proposed platform. [4]

	Fluid Fluctuation	Induced charge on surrounding	Pumping quantity
Mechanical pump	High	Low	High
Non-Mechanical pump	Low	High	Low
Circulatory platform (This method)	Low	Low	High

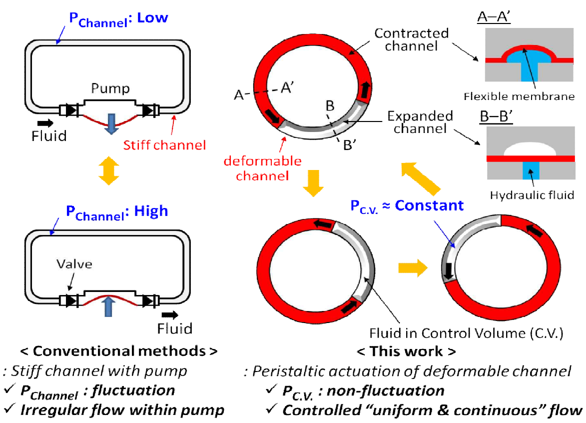

Figure 1: Closed-loop fluid circulation techniques: (Left) conventional method and (right) the proposed method in this work

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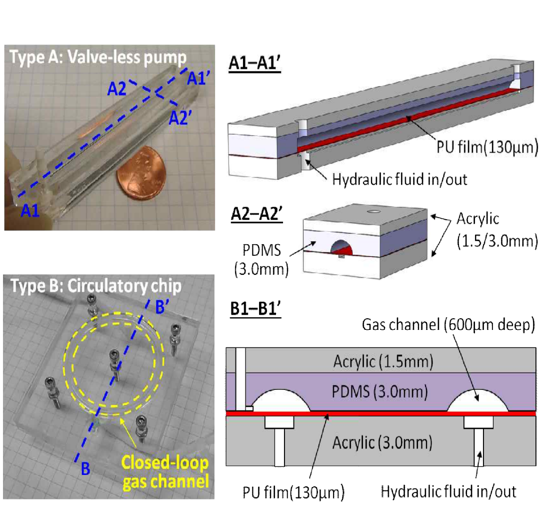

Figure 2: Photograph and cross-section image of the fabricated (top) valve-less peristaltic micropump and (bottom) fluid circulatory chip.

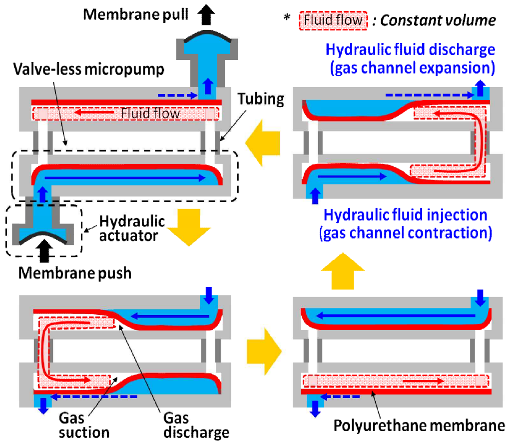

Figure 3: Schematic diagram showing the gas circulation inside the closed-loop channel; longitudinal cross-section of the fluid circulatory system that formed by connecting two valve-less peristaltic micropumps.

The operation of the circulatory flow is enabled by peristaltic deformation of the actuation membrane gradually deforming the channel along the one flow direction up to 180°. The actuation membrane movement is powered by hydraulic fluid injection and discharge of electromagnetic-hydraulic micropumps. During the operation of the closed channel, the two micropumps, located symmetric actuate with exactly 180° phase difference, resulting in the constant volume and the minimal pressure fluctuation (Fig. 3). Note that due to the 180° phase difference of the two driving hydraulic fluid flows, rapid fluctuation of pressure from each valve-less pump are attenuated.

FABRICATION

The valve-less pump was fabricated by utilizing conventional PDMS molding and bonding of multiple layers of acrylic substrates, poly-urethane film and polydimethylsiloxane (PDMS) substrate. For acrylic substrates layers, 1.5mm and 3.0mm thick acrylic substrates were used, and PDMS substrate was 3.0mm thick. A layer of 130µm thick polyurethane film, which represents fluid driving membrane, was placed between PDMS layer and 3.0mm acrylic layer (Fig. 2).

Both the acrylic substrates and polyurethane films were precisely patterned with a computer-controlled CO_2 laser cutting machine (PLS6.150D) and bonded with 25µm thick double-sided acrylic adhesive (3M 200MP). Then the PDMS substrate layer was molded, in order to include the circulatory channel shape, and was attached to the acrylic substrate by mechanical cramping with screw-bolts. This attachment is not permanent allowing the testing of different designs and shapes of PDMS channels for fast and easy. For hydraulic working fluid, silicone oil was used throughout the platform.

EXPERIMENT AND RESULTS

The flow characteristics of the proposed fluid circulatory system were evaluated using two type A valve-less micropumps connected to each other with polymer tubing (Fig. 4). Two different input signals which were altered by 180° phase difference, were generated to control two electromagnetic-hydraulic micropumps. Input signals were supplied by two function generators (Agilent, 33120A). For comparison purpose, a single type A valve-less micropump closed-loop platform, which represents conventional closed-loop flow platform, was also prepared for data collection.

Input signal conditions applied to two electromagnetic-hydraulic micropumps were as follows: 10 Vpp amplitude (max amplitude of the function generator), and three signal types (step, sinusoidal, and triangular). The absolute pressure and flow rate inside the closed-loop channel were monitored using a flow meter (OMEGA, FMA-1604A) (Fig. 4). For demonstrating the fluid circulation visually, a droplet (0.05ml) of colored DI water was injected in the closed-loop channel. Once a droplet was injected, photo and video images were recorded to verify complete circular flow.

The measurement has clearly shown that the absolute pressure fluctuation is significantly reduced compared to conventional method (Fig. 5). Particularly, the sinusoidal input case reduced the pressure differentials from 20.7torr to 4.1torr, which is 80% of reduction, while it was generating 1.1sccm of mass flow rate without any back-flow. The fabricated platform successfully demonstrated complete circular flow of the colored DI water control volume (Fig. 6). The droplet of colored DI water made a complete circulation of 173mm long circular channel in 7sec (25mm/sec) while the platform consumed 3W. And the droplet circulated 8.5 turns in 1 min (8.5 rpm).

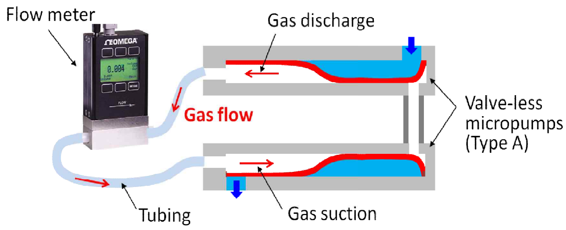

Figure 4: Experimental setup to test the proposed circulatory system with a pair of type-A micropumps.

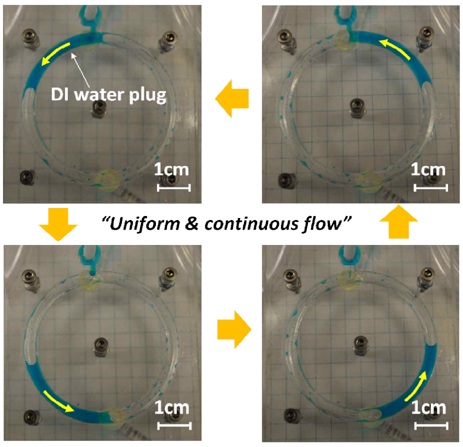

Figure 6: Photograph of the DI water plug circulation in the fabricated fluid circulatory chip (Type-B).

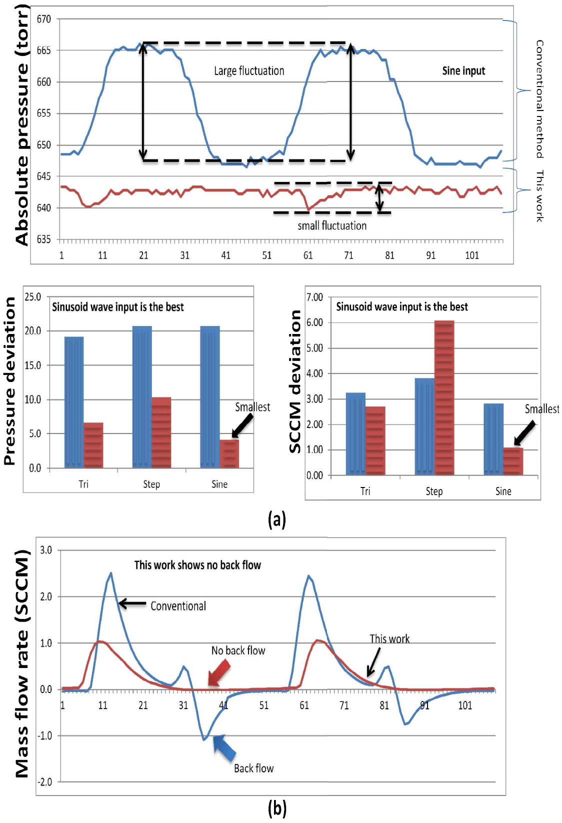

Figure 5: (a) (top) Fluctuation of abs. pressure and (bottom) pressure and flow rate deviation during the gas circulation in function of the circulation methods and input signals to the hydraulic actuator (b) fluctuation of mass flow rate under sinusoidal input wave.

CONCLUSION

This study demonstrated a new type of closed-loop micro circulation platform that produces continuous and constant-pressure fluidic circulation. The developed closed-loop micro circulation platform was operated by two valve-less micropumps connected to two electromagnetic-hydraulic micropumps. Two 180° phase altered driving hydraulic flow inputs by the valve-less micropumps significantly reduced pressure fluctuation of control volume flow compared to the conventional method. The pressure differential of proposed platform reduced pressure differentials from 20.7torr to 4.1torr, which is 80% of reduction, while it was generating 1.1sccm of mass flow rate without any back-flow. This platform can be a valuable minimizing factor of chromatography instruments, such as LC. Closed-loop constant pressure circulation micro channel can be a viable substitute to lengthy analytical column.

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