The Effects of Placement and Geometry on Thermo-Pneumatic Pumping on Centrifugal Microfluidic Compact Disc (CD) Platforms

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Abstract— **Thermo-pneumatic pumping (TPP) is used to pump fluids on a microfluidic compact disc (CD) to the center of the CD. The expansion of air during heating drives the fluid transfer during TPP. It is easy to fabricate the TPP air chamber and adjoining channel since there are no moving components in their structure and that the thermal energy is supplied to the pump through localized heating equipment. This allows the pumping process even while the disc is rotating. In this report, by changing the shape and placement of the air chamber, we demonstrate that the experimental behavior of the TPP process can be manipulated by the altering heating rate of the air chamber. The placement and geometry of the air expansion chambers affect the rate of transfer during the TPP process. These modifications allow for the customization of the TPP and for a better incorporation onto the microfluidic CD platform, enabling the platform to be more versatile, more complex in functions and countable to be implemented.**

Keywords-Microfluidic Disc; Thermo-pneumatic pumping; centrifugal microfluidic platforms; Poly(methyl methacrylate) thermal absorption;

I. Introduction

The centrifugal microfluidic platform is a portable, disposable and automated point of care diagnostic tool which has similar dimensions to a multimedia CD [1]. It is a combination of plastic layers with micro-size components such as channels and chambers. Centrifugal platforms utilize the spinning process to move and control microliters of fluids from one chamber to another through micro-size channels. This flowing and controlling process is performed without the need for syringes and physical connectors, allowing for better portability and rapid access to a diagnosis device. The rotor-based microfluidic platforms have a well-established field. Several microfluidic processes and biochemical diagnostic applications were reported, with a promise that the platform will be an essential utility in the modern world [2, 3].

Despite the significant advantages of manipulating and controlling fluids in the centrifugal microfluidic platform, the unidirectional pumping of fluids is still one of the main challenges that many researchers face in this field. This limitation is caused by the radial outward behavior of the centrifugal force that results in a pressure that pushes the liquid toward the outer ring of the microfluidic CD. As a result of this limitation, all process designs must be made within the radial length of the microfluidic CD, regardless of the number of steps the process might need. To overcome this undesirable drawback, new forces to move the liquid in directions other than outward movement need to be introduced to the centrifugal platform. The newly added direction of fluid movement allows the application of more complex designs on the CD. Pumping the liquid toward the center of the microfluidic CD during the rotation process can be one of the possible solutions that could lead to the saving of space on the microfluidic CD. If a large portion of the fluid can be pumped back to the center of the rotating CD, a better space management and performance efficiency can be achieved with lengthier assays.

Kong and Salin [4] reported a technique for solving this problem. By utilizing an external compressed air source, fluid samples can be successfully transferred to the center of a rotating CD. However, employing this technique has two major disadvantages. First, controlling the source of compressed air in order to achieve a steady flow of air can be quite challenging. Second, injection of air from outside the CD may introduce particles from the surrounding air and contaminate the fluid in the CD.

An alternative method, known as thermo-pneumatic pump (TPP) is introduced by Abi-Samra *et al* [5]. For the first time, an advantageous technique of liquid manipulation is introduced and successfully implemented on the microfluidic CD. Abi Samra *et al* [5] claim that the use of thermal expansion of trapped air may lead to a new force that pushes air towards the center of the microfluidic CD. Although various thermally actuated mechanisms have been studied, developed and used for manipulation of fluids in stationary and traditional microfluidic platforms [6-8], Abi-samra *et al* [5] is the first researcher who demonstrated and employed this technique on rotation microfluidic platforms. TPP pushes fluids away from

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the outer rim of the CD when the generated pneumatic energy is greater than the centrifugal pressure holding the fluid back. One advantage of TPP is that its operation is not limited to only hydrophilic features. This allows the use of a wide range of materials for fabrication, including polymers that are inherently hydrophobic. Furthermore, as the pumping mechanism of TPP operates on the principle of balancing the pneumatic energy and the centrifugal force on the CD, the behavior of the pump can be easily predicted and incorporated in future devices. However, since TPP requires the heating of a region of the CD, there is the issue of heating liquids embedded within the CD to a temperature above the normal storage temperature [5]. Finally, different type of heating sources, such as peripheral infrared and air heating gun, can be employed to deliver thermal energy and move fluid towards inner rim of disc.

Abi-Samra *et. al.* [5] studied the TPP performance and compared theoretical and experimental behavior of the TPP to validate their hypothesis and theoretical analysis. They employed a number of variables, such as air volume, temperature, liquid density and angular velocity to introduce a model parameter, known as k, to describe how fast the TPP absorbs thermal energy and converts it into pneumatic energy. This study examines and compares the effect of different shapes of pneumatic chamber geometry and location, as two additional variables from those employed by Abi-Samra *et. al.*, on the efficiency of TPP method. Moreover, thermal absorption behavior of the microfluidic CD surface is investigated and presented to describe the comparison of results.

II. MATERIALS AND METHODS

A. *Microfluidic CD fabriation*

AutoCAD software is employed to draw the design of the microfluidic CD layers of clear polymethylmethacrylate (PMMA) plastic which are used in the fabrication process. The layers are then bonded using pressure sensitive adhesive (PSA) sheets. The layout of the microfluidic process is milled onto the PMMA layers using a Computer Numerical Controlled (CNC) machine, and the channel features are cut from the PSA sheets using a cutter plotter.

B. *Microfluidic CD design*

Four microfluidic designs are created for the experimental work. The concept of the experiments and also design a (Fig. 1(a) are similar to the study done by Abi-Samra *et al* [5], however, in these experiments different materials, designs of microfluidic CDs, heating source, and measurement platform have been employed. The designs are shown in Fig. 1. All designs have air chambers of identical area and volume (158 µL). Each of the designs also consist of microfluidic reservoir (which contains 100µL of fluid) connected to a collection reservoir (which has a volume of 37.5µL) via a channel. The channel is aligned radially in a way that the fluid moves from the microfluidic reservoir towards the collection reservoir, while liquid flow is against the centrifugal force during the spinning process. In all designs, the cross-sectional area of the channel is approximately 63 times smaller when compared to the microfluidic reservoir. The reason for this is to simulate the transfer of liquid similarly to having a large tank with a small leak.

The experiments are conducted to evaluate the behaviors of different pump designs. The main differences within the four designs are in the geometrical shape of the air chambers, and the placement of the air chambers on the CD (either near the inner rim or near the outer rim of the CD). In designs a and b (Fig. 1(a) and Fig. 1(b)), the air chambers are located near the outer rim of the CD. In designs c and d (Fig. 1(c) and Fig. 1(d)), the air chambers are located near the inner rim of the CD. In designs a and c, the air chambers have a geometrical shape that is cylindrical, while in designs b and d, the air chambers have an odd geometrical shape.

It should also be noted that in all designs, the air chamber is placed as far as possible away from the microfluidic reservoir to avoid heating the liquid.

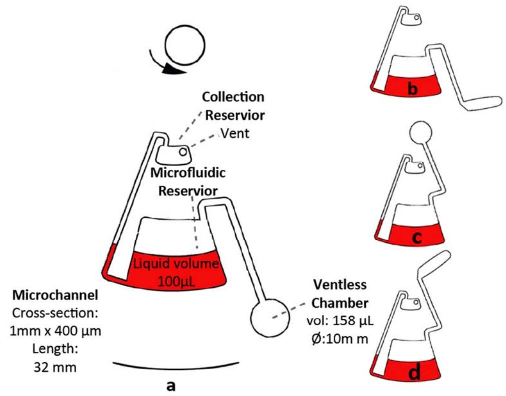

Figure 1. Microfluidic CD design: (a) cylindrical air chamber near the outer rim, (b) odd air chamber near the outer rim, (c) cylindrical air chamber near the inner rim, (d) odd air chamber near the inner rim.

C. *Experimental setup*

The assembled microfluidic CDs are tested on a specialized CD Spin Test System that allows for the control of the CD spin speed and the capturing of static images under high rotational speed (see Fig. 2). Delivery of thermal energy onto the CD is done using an air heating gun with an attached reduction nozzle (which reduces heat focusing area to 10mm in diameter).

Figure 2. Experimental setup: (i) IR thermal meter, (ii) smart camera (iii) rpm sensor, (iv) computer, (v) air heating gun

The hot air is delivered from a distance of 15mm above the rotating CD. The delivery of the heat is measured using an infrared (IR) thermal meter. At the start of every experiment, the liquid is loaded on the CD (into the microfluidic chamber) and sealed with tape. The chamber is fully sealed to ensure that no hot air escapes through the loading hole of the microfluidic reservoir. The air heating gun is then aligned above the heating area and the CD is spun up.

III. Results and Analysis

A. Heating Profile of the CD

Experiments are performed to determine the heat absorption pattern of the CD. The experiments are conducted at a heating temperature of 130°C and a disc rotation speed of 300 RPM. The temperature of the CD is measured for 5 minutes, and the result is shown in Fig. 3.

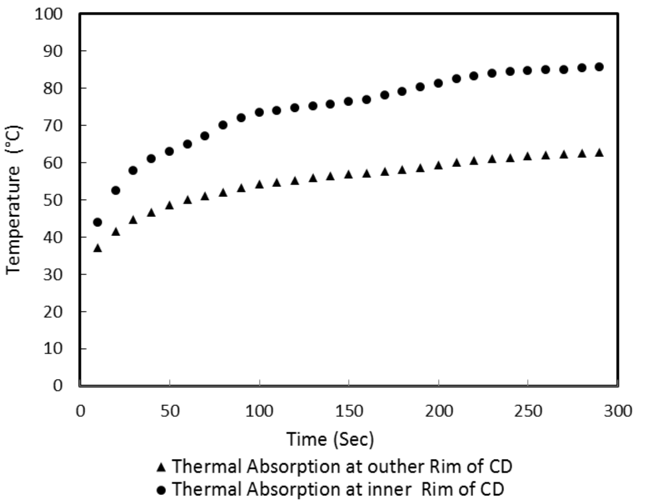

Figure 3. PMMA's thermal absorption behavior

According to the results, shown in Fig. 3, the area at the outer rim of the CD has slower and less thermal abortion in comparison with the area near the center of the CD. The reason is due to higher directional speed of the outer rim of the CD compared to an area that is closer to the center of the CD. Thus, in each cycle, any particular area near the outer rim of the CD is exposed to heat for a shorter time, as compared to a similar heated area near the inner rim of the CD.

B. Placement and Geometry Effects

Experiments are conducted to study the following effects on the TPP:

- The effect of the location of air chamber on pumping behavior
- The effect of the geometry of the air chamber on pumping behavior

All experiments are conducted at a heating temperature of 130°C and a disc rotation speed of 300 RPM. Thermal energy is applied to the air chamber and the movement of liquid is observed as shown in Fig. 4. Heat is applied until the liquid is observed to fill the collection reservoir. As the fluid is pumped out of the microfluidic reservoir into the channel and towards the center of the CD, continuous heating is required to produce more air pressure and to constantly pump the liquid into the collection chamber. The same procedure has been repeated for all designs (see Fig. 1) and the required heating time for the TPP to deliver liquid and fill the collection chamber has been recorded and exhibited in Fig. 5.

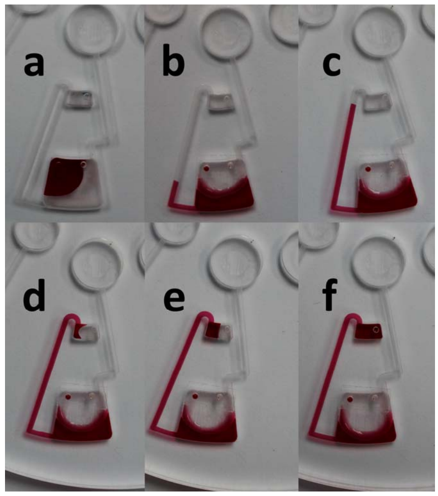

Figure 4. Thermo-pneumatic pumping of liquid from the microfluidic reservoir to the collection reservoir while the CD is rotating at 300 rpm. (a) initial state, (b) liquid enters the channel, (c) liquid travels up the channel towards the center of the CD, (d) liquid enters the collection reservoir, (e-f), liquid fills the reservoir.

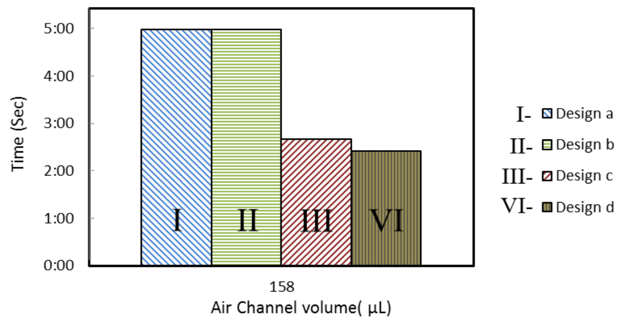

Figure 5. Record of required time for pumping of liquid to fill the collection reservior (design a, b, c, and d corresponds to designs shown in Fig. 1).

The results of the effect of the air chamber location on TPP behavior indicate that placing the air chamber closer to the inner rim of the CD (design c and d) significantly reduces the time needed to transfer the liquid from the microfluidic reservoir to the collection reservoir. This is in agreement with the results shown in Fig. 3, where the area nearer to the outer rim of the CD slowly absorbs heat as compared to the area closer to the inner rim of the CD.

Comparing air chambers of different shapes, the results show that in designs a and b, the geometry of the air chamber has no effect on liquid transferring time. However, comparing designs c and d indicates that using an air chamber of odd geometry shape (design d) results in a small reduction in transfer time.

Among the four CD designs shown in Fig. 1, the result in Fig. 5 shows that design d requires the shortest liquid transfer time. This is due to the facts that (i) the design has an air chamber which is closer to the inner rim of the CD, and as shown in Fig. 3, the heat absorption is higher on areas near the inner rim of the CD, (ii) the air chamber in design d has an odd geometry shape, which exposes it to the heat source for a longer period of time, as compared to an air chamber with a cylindrical shape. It is noticeable that, fact ii is also true about design b.

The similarity of liquid transferring time between designs a and b is due to the high inhomogeneous air pressure distribution in air chamber b. This fact is also true about design d, but because of the faster thermal absorption and shorter liquid transferring time, it fails to overcome the mentioned fact (ii). Observing TPP behavior of designs a and b shows that design b starts pumping liquid by a higher acceleration, but as time goes by, it has a higher liquid transferring deceleration in comparison with design a. Due to fact ii, the odd air chamber (design b), at the beginning, has faster thermal absorption compared to design a, and, therefore, there is faster liquid pumping. However, when temperature increases very slowly, higher inhomogeneity of air pressure at various areas of the odd air chamber in design b causes a reduction in output air pressure towards the channels as compared to that of design a. Particularly in design b, this effect and also fact (ii) counterbalance each other in a way to produce results similar to design a, but employing different sizes of air chambers for design a and b can produce unequal liquid transferring time as required to fill the reservoir chamber.

IV. CONCLUSIONS

The centrifugal microfluidic CD only moves liquid from the inner rim towards the outer rim of the CD. This characteristic limits the number of processing steps that can take place on the CD before the fluids reach the outer edge of the CD. Employing the TPP method allows for the pumping of fluid from areas near the outer rim of the CD back toward areas near the inner rim of the CD. The main benefits of the TPP method are the improvement of real-estate usage on the CD, and the ability of the TPP to operate regardless of if the CD is made of hydrophilic or hydrophobic materials. In this paper, we have shown that the behavior of the TPP can be predicted accurately, and can be further manipulated by selective placement of the air chamber on the CD. Also, the geometrical shape of the air chamber also affects the TPP behavior. However, changing the geometry produces new variables thus reducing the simplicity of analysis, controlling the liquid flow, and TPP behavior. As most of the diagnosis methods on the microfluidic CD platform rely on timing techniques to control the flow of fluid on the CD, the implementation of TPP is suitable as an addition to the pumping method.

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