

## Multi-Level 3D Implementation of Thermo-Pneumatic Pumping on Centrifugal Microfluidic CD Platforms \*

Tzer Hwai Gilbert Thio, Fatimah Ibrahim, *Member, IEEE*,  
Wisam Al-Faqheri, *Student Member, IEEE*, Norhayati Soin, *Member, IEEE*,  
Maria Kahar Bador Abdul Kahar, Marc Madou, *Member, IEEE*

**Abstract**— Thermo-pneumatic (TP) pumping is a method employing the principle of expanding heated air to transfer fluids back towards the CD center on the centrifugal microfluidic CD platform. While the TP features are easy to fabricate as no moving parts are involved, it consumes extra real estate on the CD, and because heating is involved, it introduces unnecessary heating to the fluids on the CD. To overcome these limitations, we introduce a multi-level 3D approach and implement forced convection heating. In a multi-

level 3D CD, the TP features are relocated to a separate top level, while the microfluidic process remains on a lower bottom level. This allows for heat shielding of the fluids in the microfluidic process level, and also improve usage of space on the CD. To aid in future implementations of TP pumping on a multi-level 3D CD, studies on the effect of heat source setting, and the effect of positioning the TP feature (it distance from the CD center) on CD surface heating are also presented. In this work, we successfully demonstrate a multi-level 3D approach to implement TP pumping on the microfluidic CD platform.

\* This research is financially supported by University of Malaya, Ministry of Higher Education High Impact Research (UM/HIR/MOHE/ENG/05), and University of Malaya Research Grant (UMRG: RG023/09AET). The authors would like to acknowledge Prof. Dr. Noorsaadah Abd Rahman from Department of Chemistry, Faculty of Science, University of Malaya and her grant "Hits-to-Lead: Designing Dengue Virus Inhibitors, National Biotechnology Directorate (NBD) Initiative-Malaysian Institute of Pharmaceuticals and Nutraceuticals (IPharm), Ministry of Science, Technology and Innovation (MOSTI IPHARM 53-02-03-1049)" for partially sponsoring the initial set-up of the CD Spin Test System. Marc Madou acknowledges support of National Institute of Health (grant 1 R01 AI089541-01), and support of WCU (World Class University) program (R32-2008-000-20054-0) through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology.

Tzer Hwai Gilbert Thio is with the Medical Informatics & Biological Micro-electro-mechanical Systems (MIMEMS) Specialized Laboratory, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. He is also with the Faculty of Science, Technology, Engineering and Mathematics, INTI International University, Persiaran Perdana BBN, Putra Nilai, 71800 Nilai, Negeri Sembilan, Malaysia. (E-mail: gilbert\_thio@hotmail.com).

Fatimah Ibrahim is with the MIMEMS Specialized Laboratory, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. (Fax: 603 7967 4579; Tel: 603-7967-6818; E-mail: fatimah@um.edu.my).

Wisam Al-Faqheri is with the MIMEMS Specialized Laboratory, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. (E-mail: wisamfakhri83@yahoo.com).

Norhayati Soin is with the MIMEMS Specialized Laboratory, Department of Biomedical Engineering, and with the Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. (E-mail: norhayatisoin@um.edu.my).

Maria Kahar Bador Abdul Kahar is with the Medical Informatics & Biological Micro-electro-mechanical Systems (MIMEMS) Specialized Laboratory, Department of Biomedical Engineering, Faculty of Engineering, and with the Department of Medical Microbiology, Faculty of Medicine, University of Malaya, 50603 Kuala Lumpur, Malaysia. (E-mail: mariakb@um.edu.my)

Marc Madou is with the MIMEMS Specialized Laboratory, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. He is also with the Department of Biomedical Engineering, and Department of Mechanical and Aerospace Engineering, University of California, Irvine, Irvine, 92697, United States. (E-mail: mmadou@uci.edu)

### I. INTRODUCTION

The centrifugal microfluidic compact disc (CD) platform allows for miniaturization and full automation of complex diagnostic processes. The core component of the platform is the plastic CD which is low cost and portable, making it suitable for use as a point-of-care diagnostic tool [1-3]. The CD contains engraved micro-size chambers and channels, and when structured in various layouts it makes it possible to control the flow sequencing of small volumes of fluids on the CD. The advantage of the CD platform is that fluids are pumped by the centrifugal force generated by the spinning of the CD. It operates independently of syringes or physical connectors, and does not require any external pump or actuator for executing any microfluidic process. The standalone aspect of the platform allows for better portability, operability, and disposability. The flexibility in the design of the micro features on the platform allows for a wide range of processes such as valving, mixing, metering, volume splitting, separation, siphoning, flow control etc [1-3]. This allows for a wide range of application in the field of biomedical engineering to be developed on the platform. Examples include the detection of antigen and antibody [4-6], cell lysis and plasma separation [3, 7] and polymerase chain reaction (PCR) [8, 9].

However, because the centrifugal force is directed outward from the CD center, the platform only allows the flow of fluids from the CD center towards the CD edge. This limits the number of steps a microfluidic process can integrate before fluids reach the CD edge. To overcome this limitation, Abi-Samra et al [10] had adapted a thermo-pneumatic (TP) pumping method [11, 12] onto the CD platform. The method incorporates a sealed TP air chamber that is connected through an air channel to a source liquid chamber near the CD edge. The TP air chamber, air channel, and the microfluidic process are fabricated in the same layer of plastic. When thermal energy is applied to the TP air chamber, thermal expansion of air occurs and this generates a positive pressure built-up in the connected source liquid

chamber. The increasing pressure built-up then pushes liquid from the attached source liquid chamber towards a destination liquid chamber nearer to the CD center (see Fig. 1).

However, a TP pump consumes considerable space on the CD. For timely pumping of liquid from the CD edge towards the CD center, the air chamber size needs to be at least equal to the volume of liquid to be pumped. This significantly increases the amount of space needed on the CD. Another issue with TP is the problem of heating unintended areas on the CD. As the heat source delivers heat along a circular path on a spinning CD, embedded fluids that are within the circular heating path or in close proximity to it may be exposed to unnecessary heating.

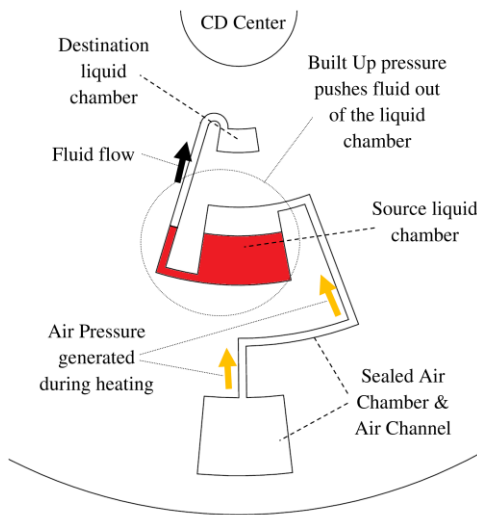


Figure 1. Principles of thermo-pneumatic pumping on the microfluidic CD platform. (In this illustration, the air chamber and air channel are engraved in the same layer as the microfluidic process)

To address the spatial and heating problems, we introduce a multi-level 3D CD design, and implement forced convection heating. In our design, the CD consists of more than one level: the top level contains the TP features, and the bottom level contains the microfluidic process. The two levels are connected by through holes for air exchange. During heating, the forced convection heating only heats the CD surface. In our report, we describe how the multi-level 3D CD is fabricated, and demonstrate that TP pumping can be implemented successfully on a multi-level 3D CD while addressing the spatial and heating issues.

## II. METHODOLOGY

### A. Multi-Level 3D CD Fabrication and Design

To implement the TP pump on a multi-level 3D CD, three plastic discs were fabricated and bound using two sheets of adhesive material. The fabrication technique is similar to that used for single-level CDs in our previous work [13]. The plastic discs are made of Polymethyl methacrylate (PMMA) material, and the adhesive material is a custom made pressure sensitive adhesive (PSA). The top disc is a 2mm thick PMMA layer that contains no features. The middle disc is 4mm thick and contains only the TP air

chamber engraved on the top surface, and a through hole for air exchange (see Fig. 2(a)). The bottom disc is 2mm thick and contains the microfluidic process features engraved on the top surface. The PSA sheets between the respective discs have TP or microfluidic process features identical to the corresponding discs cut out. Once all discs and PSA sheets are fabricated and cut, they are pressed-bound together using a custom made press roller. The combined TP and microfluidic process features is illustrated in Fig. 2(a).

Placing the TP air chamber directly above the liquid chamber provides two advantages: (i) the air channel is reduced to a mere through hole, reducing the space required for an additional air channel, (ii) by placing the TP chamber in the top level, only the TP air chamber is effectively heated by the forced convection heat source.

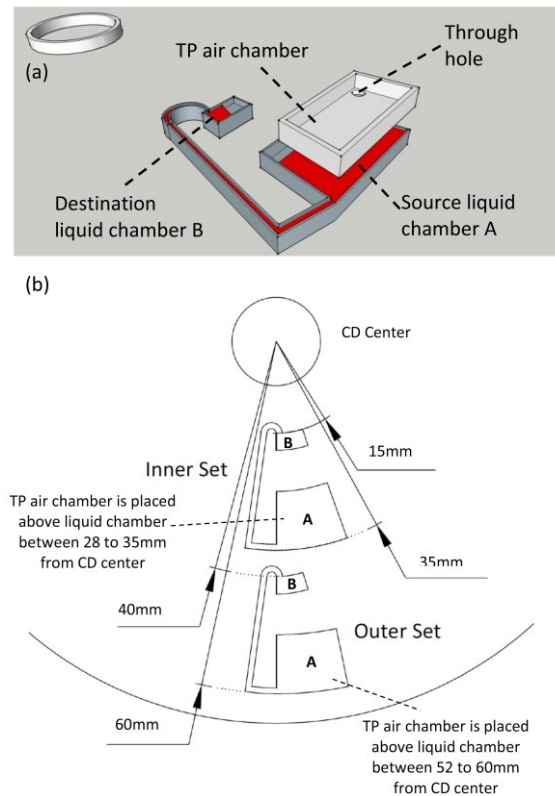


Figure 2. (a) 3D drawing of the implementation of TP pumping on a multi-level 3D CD (b) CD design to evaluate the effect heat source setting, and positioning of TP air chamber on the CD: Inner Set is close to the CD center, while Outer Set is closer to the edge of the CD

Fig. 2 describes the design of the 3D CD fabricated for the experimental work. As shown, the design consists of a TP air chamber, source and destination liquid chambers A and B, and a channel connecting the two chambers. Chamber A is connected to the TP air chamber via the through hole. During heating, the heated air in the TP air chamber expands and results in positive pressure acting on the liquid in chamber A. This positive pressure pushes the liquid out chamber A towards chamber B which is closer to the CD center.

To study the effect of the placement of the TP air chamber on the CD with respect to the CD center, two sets of

experiments were designed on the CD (see Fig. 2(b)). An Inner Set is placed at a radial position between 15 to 35mm from the CD center, and an Outer Set is positioned between 40 to 60mm from the CD center. In both sets, liquid is pumped over a radial distance of 20mm from chamber A towards the CD center to chamber B.

### B. Experimental Setup

Experimental results are recorded using a customized CD spin test system (see Fig. 3). CDs are locked onto a motorized spinning module controlled by a LabVIEW program on a computer system. Image capture by the LabVIEW program is performed using a high speed camera, and a connected digital RPM triggers image capturing at one image per revolution.

Forced convection heating is implemented using a modified industrial grade hot-air gun (model: Bosch GHG 630 DCE). The hot-air gun has a digital temperature controller that allows for heat settings in steps of 10°C, and is fitted with a focusing nozzle to provide a small heating area of 1cm<sup>2</sup> when placed 1cm above the CD surface. An Infrared (IR) thermometer (model: Smart Sensor AR550) is used to measure the CD surface temperature.

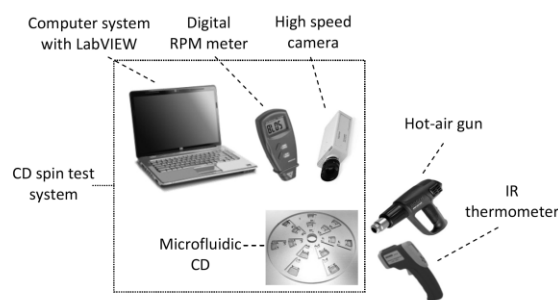


Figure 3. Experimental Setup: CD spin test system consisting of computer system installed with LabVIEW, digital RPM meter, and high speed camera; forced convection heating is implemented using a hot-air gun, and CD surface temperature is measured using an IR thermometer.

### C. Experimental Methods

In all experiments, the source liquid chamber A is loaded with 80μL of colored deionized (DI) water (at a ratio of 10 parts DI water to 1 part food dye). The CD is then loaded onto the CD spin test system, with the heat source placed above the path of the TP air chamber. The CD is spun at 300rpm, and CD surface temperature is air cooled to room temperature (25°C) before the heat source is powered ON. The CD surface temperature is measured once every 1.5 minutes, and the transfer of liquid from the source liquid chamber A to destination chamber B is also observed.

To determine the effects of heat source settings on CD surface heating and liquid transfer, the Inner set is tested at heat source settings of 130 °C and 160°C. The result is shown in Fig. 5(a). To explore the effect of TP air chamber placement (relative to the CD center), the Inner and Outer sets are both tested at a heat setting of 160°C. The result is shown in Fig. 5(b).

## III. RESULTS AND DISCUSSION

### A. TP Pumping on a Multi-Level 3D CD

The sequence of TP pumping of liquid from source chamber A to destination chamber B nearer to the CD center is shown in Fig. 4. Initially, the liquid is loaded into chamber A (Fig. 4(a)) and the CD is spun at 300rpm. As heat is directed to the TP air chamber, the heated air expands and pushes onto the liquid in the attached chamber A below. This increasing pressure pushes the liquid from chamber A into the connecting channel towards the opening into chamber B (Fig. 4(b)). Finally, as the TP pump continues to supply expanding air into chamber A, the liquid flows into chamber B till it is full (Fig. 4(c)). The result shows that TP pumping can be implemented successfully on a multi-level 3D CD. The time it takes for the liquid transfer shown in Fig. 4(b) and (c) is recorded in Fig. 5, and the effects of heat source settings and the placement of TP air chamber will be discussed in the next two sections.

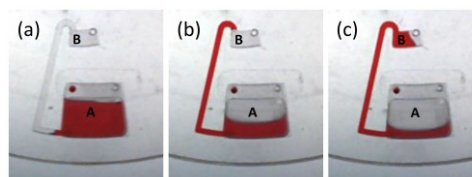


Figure 4. Sequence of TP pumping of liquid from source liquid chamber A to destination liquid chamber B on a multi-level 3D CD. (a) Initial state of liquid loaded into chamber A prior to heating. (b) Liquid is pushed from chamber A towards the channel opening into chamber B. (c) Continuous heating of TP air chamber pushes liquid into chamber B.

### B. Effects of Heat Source Settings

The measured CD surface temperature when using heat source settings of 130 °C and 160°C is shown in Fig. 5(a). The result shows that the CD surface temperature rises rapidly from room temperature when the heat source is powered ON, and then gradually saturates after 9 minutes. For a heat source setting of 130°C, the CD surface temperature saturates around 65 °C, while for a setting of 160°C the saturation temperature is around 75°C. The result indicates a thermal transfer efficiency of approximately 45% ~ 50% at these two settings.

For heat source setting of 130°C, the liquid reaches the channel opening into chamber B at 7.42 minutes, and starts filling the chamber at 8.42 minutes. In both occurrences, the CD surface temperature was measured to be approximately 66°C. At the heat source setting of 160°C, the values are measured to be 4.17 minutes and 5.17 minutes, at temperatures of 72°C and 74°C respectively. The results indicate that a higher heat source setting provides more effective heating of the TP air chamber, resulting in quicker expansion of the heated air, and faster transfer of liquid from source liquid chamber A to destination chamber B.

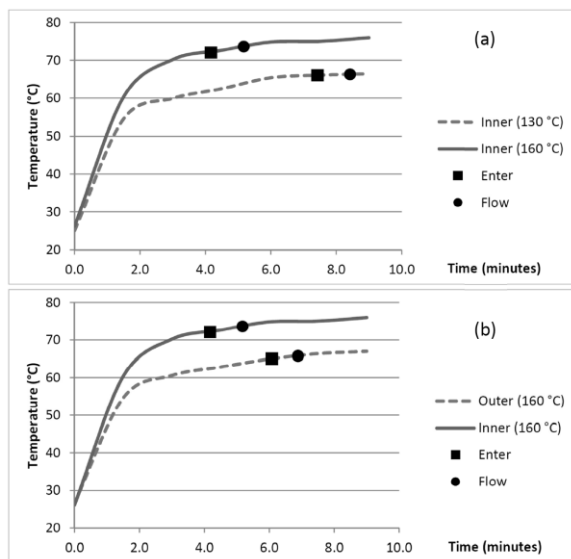


Figure 5. Experimental results. (a) Effect of heat source setting on CD surface temperature and liquid transfer. (b) Effect of TP air chamber placement on the CD on CD surface temperature and liquid transfer.

### C. Effects of TP Pump Placement

The measured CD surface temperature when the TP air chamber is placed between 28-35mm (Inner Set) and between 52-60mm (Outer Set) from the CD center is shown in Fig. 5(b). For the Inner set, the liquid starts entering Chamber B after 4.17 minutes, and starts filling the chamber after 5.17 minutes, at surface temperatures of 72°C and 74°C respectively. For the Outer Set, the corresponding values are measured to be 6.08 minutes and 6.88 minutes, both at a temperature of approximately 65°C.

Unlike typical centrifugal microfluidic processes on the CD where the effect of the centrifugal force increases with increasing distance from the center of the CD, the results show that for TP pumping, the pumping effect increases with decreasing distance from the center of the CD. The effect of the placement of the TP air chamber can be explained as follows:

- As the CD spins, the hot-air gun is directed along a circular path on the CD. The heating path for the Inner Set is smaller than the heating path for the Outer Set. Hence for each rotation of the CD, the TP air chamber on the Inner Set receives more heat compared to the Outer Set.
- The centrifugal pressure on the liquid is directly proportional to the distance of the liquid from the center of the CD [1-3]. As the liquid chambers on the Inner Set are closer to the center of the CD compared to the Outer Set, the centrifugal pressure acting on the liquid is less. Hence less expanding air is needed for the Inner Set compared to the Outer Set

## IV. CONCLUSION

We presented a multi-level 3D approach to implementing TP pumping on the microfluidic CD platform. Experimental results indicate that a higher heat source setting and

placement of the TP air chamber nearer to the CD center provides faster liquid transfer. However, to operate the pump at lower temperatures for biological applications that are sensitive to heat, the placement of the TP air chamber should be placed nearer to the CD edge, and the heat source setting lowered. In general, the multi-level 3D approach has been demonstrated to be suitable for providing heat shielding to fluids in the microfluidic process level, and allowing for easy implementation of TP pumping on the top level without the need to sacrifice space otherwise required for the microfluidic process.

## REFERENCES

- [1] M. Madou, J. Zoval, G. Jia, H. Kido, J. Kim, and N. Kim, "Lab on a CD," *Annual Review of Biomedical Engineering*, vol. 8, pp. 601-628, 2006.
- [2] J. V. Zoval and M. J. Madou, "Centrifuge-based fluidic platforms," *Proceedings of the IEEE*, vol. 92, pp. 140-153, 2004.
- [3] J. Ducr e, S. Haeberle, S. Lutz, S. Pausch, F. Von Stetten, and R. Zengerle, "The centrifugal microfluidic Bio-Disk platform," *Journal of Micromechanics and Microengineering*, vol. 17, pp. S103-S115, 2007.
- [4] B. S. Lee, J. N. Lee, J. M. Park, J. G. Lee, S. Kim, Y. K. Cho, and C. Ko, "A fully automated immunoassay from whole blood on a disc," *Lab on a Chip*, vol. 9, pp. 1548-1555, 2009.
- [5] F. Ibrahim, A. A. Nozari, P. Jahanshahi, N. Soin, N. A. Rahman, S. Z. M. Dawal, M. K. B. A. Kahar, K. A. Samra, and M. Madou, "Analysis and experiment of centrifugal force for microfluidic ELISA CD platform," in *Proceedings of the IEEE Conference on Biomedical Engineering and Sciences (IECBES)*, Kuala Lumpur, 2010, pp. 466-470. DOI 10.1109/IECBES.2010.5742282
- [6] N. A. Yusoff, N. Soin, and F. Ibrahim, "Lab-on-a-disk as a potential microfluidic platform for dengue NS1-ELISA," in *Proceedings of IEEE Symposium on Industrial Electronics & Applications (ISIEA)* Kuala Lumpur, 2009, pp. 946-950. DOI 10.1109/ISIEA.2009.5356330
- [7] H. Kido, M. Micic, D. Smith, J. Zoval, J. Norton, and M. Madou, "A novel, compact disk-like centrifugal microfluidics system for cell lysis and sample homogenization," *Colloids and Surfaces B: Biointerfaces*, vol. 58, pp. 44-51, 2007.
- [8] J. Burger, A. Gross, D. Mark, F. Von Stetten, R. Zengerle, and G. Roth, "IR thermocycler for centrifugal microfluidic platform with direct on-disk wireless temperature measurement system," in *Proceedings of the 16th International Solid-State Sensors, Actuators and Microsystems Conference, TRANSDUCERS'11*, Beijing, China, 2011, pp. 2867-2870
- [9] M. Amasia, M. Cozzens, and M. J. Madou, "Centrifugal microfluidic platform for rapid PCR amplification using integrated thermoelectric heating and ice-valving," *Sensors and Actuators, B: Chemical*, vol. 161, pp. 1191-1197, 2012.
- [10] K. Abi-Samra, L. Clime, L. Kong, R. Gorkin Iii, T. H. Kim, Y. K. Cho, and M. Madou, "Thermo-pneumatic pumping in centrifugal microfluidic platforms," *Microfluidics and Nanofluidics*, vol. 11, pp. 643-652, 2011.
- [11] K. Handique, D. T. Burke, C. H. Mastrangelo, and M. A. Burns, "On-chip thermopneumatic pressure for discrete drop pumping," *Analytical Chemistry*, vol. 73, pp. 1831-1838, 2001.
- [12] S. M. Ha, W. Cho, and Y. Ahn, "Disposable thermo-pneumatic micropump for bio lab-on-a-chip application," *Microelectronic Engineering*, vol. 86, pp. 1337-1339, 2009.
- [13] T. H. G. Thio, S. Soroori, F. Ibrahim, W. Al-Faqheri, N. Soin, L. Kulinsky, and M. Madou, "Theoretical development and critical analysis of burst frequency equations for passive valves on centrifugal microfluidic platforms," *Medical & Biological Engineering & Computing*, 2013 DOI 10.1007/s11517-012-1020-7