

# SWITCHING OF SECONDARY FLOW BEHAVIOR ON CENTRIFUGAL MICROFLUIDICS

Yoshiaki Ukita, Yuzuru Takamura

School of Materials Science, Japan Advanced Institute of Science and Technology (JAIST), Japan

## ABSTRACT

This paper reports how secondary flow behaves in centrifugal microfluidics, and how we demonstrated the controlling of the flow behavior. We observed the secondary flow in a microchannel on a centrifugal microfluidics. The microchannel is patterned along the edge of the disk. While the contribution of Dean force on the generation of secondary flow is expected, however we conclude that the Coriolis force is major force to induce the secondary flow. To estimate the possibility of secondary flow controlling, centrifugal microfluidic devices are developed for the investigation of secondary flow behaviors. As the result of series of investigations, we found out that the secondary flow can be controlled by changing spinning rate.

## KEYWORDS

secondary flow, centrifugal microfluidics, Coriolis force.

## INTRODUCTION

In the recent development of microfluidics, the use of secondary flow in curved microchannel with high flow rate is explored for the new science and technology, especially for the application of particle separation. [1-4] For example Ali Asgar S. Bhagat et al. applied Dean Flow Fractionation (DFF) for the isolation of large particles from a suspension of various particles mixture. [2] Xiaole Mao et al. realized three-dimensional hydrodynamic focusing on a planar microchannel network by utilizing Dean flow. [4]

Beside, Dean force-induced secondary flow is the typical origin of secondary flow in general microfluidics, however it has been reported that the resemble secondary flow is observed in the studies of centrifugal microfluidics. J. Ducree et al. reported Coriolis force induced secondary flow on centrifugal microfluidics. [5, 6] They applied this phenomenon on multilamination of flow for micromixing. For the application of this secondary flow, to understand the difference of flow characteristics between Dean force-induced and Coriolis force induced secondary flow and to estimate the possibility of controlling the flow behavior is important for development of new applications. In this paper, we designed microchannel consist of radial and circular arrangement for the controlling of secondary flow, and we investigated the difference of secondary flow behavior by the difference of spinning speed of disk and flow rate. Finally we demonstrated flow mode switching of the secondary flow by switching spinning speed from low speed to high speed.

## EXPERIMENT

Fig. 1 shows schematic illustration and photograph of the microfluidic chip, which we designed for the experiment. To change flow speed in the same spinning speed, the length and width of radially arranged microchannel (resistivity control part) is designed in variations. The dimension of circular channel part is designed to be same for all chips.

Victoria blue and Safranin are purchased from Sigma and Wako respectively. They are diluted in distilled water with concentration of 0.1% in weight to obtain blue color and red color ink. Polydimethylsiloxane (PDMS; Silpot 184) is purchased from Toray Dowcorning. Commercially available blank CD media is used as a substrate of the device. To obtain clear transparent

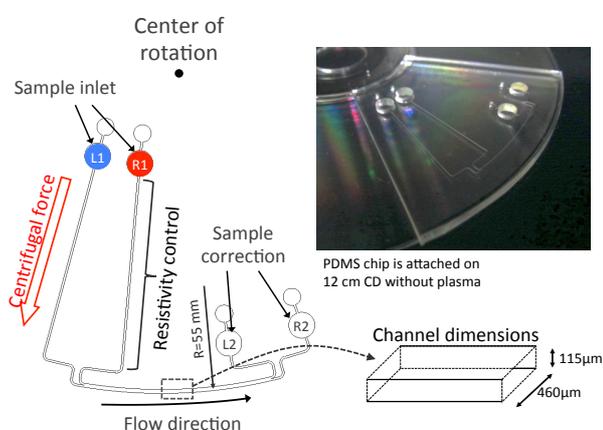


Figure 1. Schematic illustration and photograph of microfluidic chip. Flow speed is controlled by changing width and length of resistivity control part.

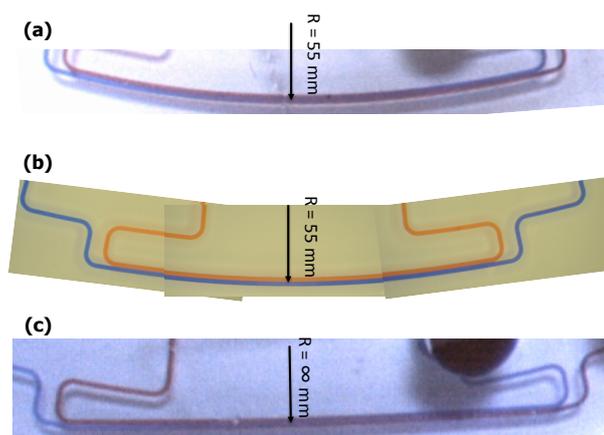


Figure 2. Observed secondary flow behavior in microchannel. Channel dimensions and  $Re$  number are set at same. Other conditions are as follows. (a) 1500 rpm,  $De = 5.8$  (b) 0 rpm,  $De = 5.8$  (c) 1500 rpm,  $De = 0$

disk, coating film was peeled off as follow. The coating film of the CD was cut with knife and the coating film was peeled by adhesive tape. Then the disk was cleaned using ethanol followed by rinse with water. Finally white adhesive tape is pasted on the surface of CD for better visibility of observation with strobe scope. Thick negative photoresist (SU-8) and SU-8 developer was purchased from Nipponkayaku Co., Ltd.. 4-inch silicon wafer was used for the prototyping of SU-8 mold. The pattern of the device was designed using Auto CAD and converted into Adobe Illustrator file. The converted data was printed on the transparent film with commercial high-resolution printing service.

A microfluidic device made of PDMS (3 mm in thickness) are fabricated by the conventional softlithography method. [7] First of all, the SU-8 mold pattern was fabricated on the silicon wafer as follows. 4 inch silicon wafers were hard baked on a hot plate more than 5 min at 200 °C and SU-8 (3050) is spincoated to obtain 100 um thick photoresist film. Then the substrate is baked for 1 min at 65 °C and 45 min at 95 °C to obtain dry film of monomer. Then the film of SU-8 is exposed to UV light using prepared photomask for 45 sec. The exposed substrate is baked for 1 min at 65 °C followed by 5min at 95 °C for the polymerization of exposed SU-8. The baked substrate is immersed into SU-8 developer and rinsed isopropylalcohol finally dried with gentle nitrogen stream. PDMS monomer and catalyst were mixed with mass ratio of 10:1 in and pored on the SU-8 mold and baked at 75 °C for 1.5 hr. The polymerized PDMS film (3 mm in thickness) was peeled form the substrate and cut along the designed shape with knife. The liquid reservoirs and air vent holes were punched with puncher.

The experiments are initialized as follows. The PDMS chips were cleaned with ethanol and water. The water droplets are blown off by nitrogen splay, and the chips are left few tens minutes for the complete drying. The PDMS chips are attached onto the CD by utilizing self-adhesion of PDMS. The maximum rate that can be applied in the experiment is 3000 rpm. Then all fluidic channel is filled with distilled water and blue ink and red ink samples (20 ul in volume) are loaded into the left hand inlet (L1) and right hand inlet (R1). All reservoirs are sealed with adhesive tape. The device is placed in a custom-made spinner and spun at a constant rate ranging 1000 to 3000 rpm. The acceleration of the spinning is 5000 rpm/s.

To analyze the significance of secondary flow, we implemented two kind of analysis. To visualize the flow behavior on the spinning disk we developed strobe scope system as generally used in the development of centrifugal microfluidics. [5, 6] For more quantitative discussions we corrected mixture of the inks from the sample correction reservoirs (L2 and R2). The recovered mixtures are diluted 100-times and absorbance spectrum is measured. The absorbance spectrum of the mixture was analyzed based on standard spectrums of blue ink and red ink by using solver function of microsoft excel.

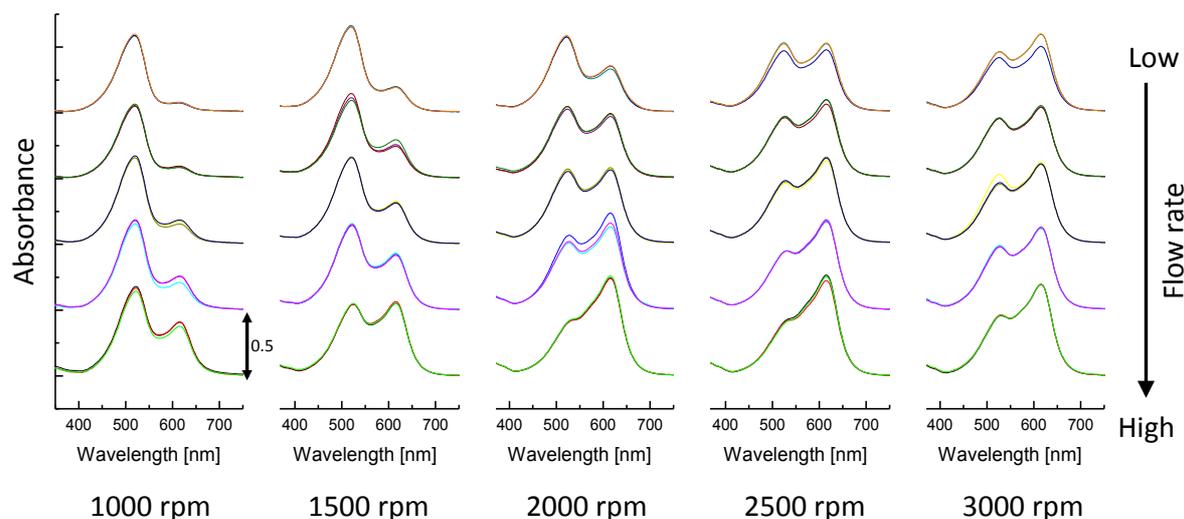


Figure 3. Simulated flow behaviors. The figures on left hand are bird-eye view and right hand are corresponding concentration distribution and flow vectors in cross-section. The flow rate in all simulation was assumed to be 14 ul/sec.

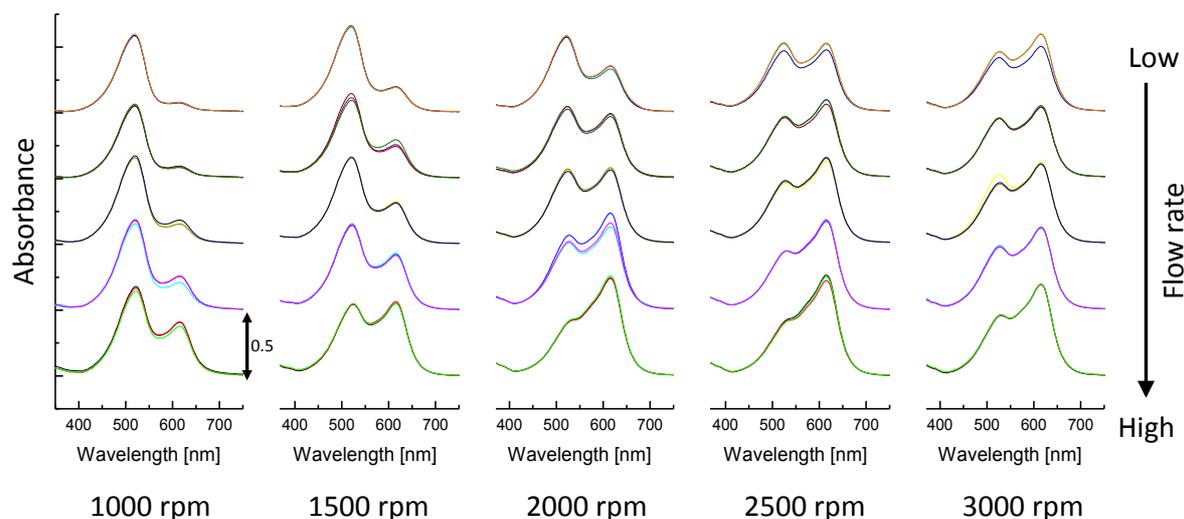


Figure 4. Measured absorbance spectrum of corrected ink in sample flows in L2 reservoir. Origin of peak around 500 nm is Safranin and 610 nm is Victoria Blue. Three experiments are carried out for each conditions.

## RESULTS

Figure 2 shows observed secondary flow behaviors in the microchannel. Figure 2 (a) and 2 (c) are taken under spinning condition at 1500 rpm and both of them exhibit twisting of the flow due to secondary flow. However, in case of fig. 2 (b), which taken under same flow rate without spinning, does not exhibit secondary flow at all. These observations suggest that the Dean force, which arise from centrifugal force due to the curve of the microchannel, does not have significant contribution to induce the secondary flow but the other kind of force arise from spinning of the CD have (e. g. Coriolis force).

Figure 3 shows simulated result of flow behavior, which carried out by considering Coriolis force as volumetric force. The result agrees with observed flows suggesting contribution of Criolis force on the secondary flow. Fig. 4 shows mixing ratio of inks of corrected samples in L2 reservoir (see fig. 1) and corrected sample ratio depends on both of flow rate and spinning speed. Thus we conclude that the secondary flow is induced by Coriolis force and it is possible to control by controlling flow rate and spinning speed. For example, in the case of relatively low flow rate and slow spinning speed (0.096 ul/sec, 1000 rpm) the 90% of the content is red color suggesting suppression of secondary flow, however in the case of relatively high flow rate and high spinning speed (3000 rpm, 0.888 ul/sec) more than 60% of the content is blue color suggesting significant secondary flow.

Series of the experiments enables to build up knowledge and experience to control and design the secondary flow behavior in the centrifugal microfluidics, owing this we currently succeeded in to control the flow switching on the same platform using change of spinning speed as shown in fig. 5, which expected to contribute on applications such as continuous cell separation, and interface reactions.

## CONCLUSIONS

We have investigated the origin of secondary flow and conclude that the observed secondary flow behavior is generated due to the major contribution of the Coriolis's force while Dean force is not significant. Therefore it is controlled by the control of spinning speed and flow rate because Coriolis force is proportional to both of them. However secondary flow is more sensitive to the spinning speed than flow rate. Finally we successfully demonstrated the flow mode switching of the secondary flow. The knowledge of the laminar stability on the centrifugal microfluidics built in this study can be a foundation of new development of application of centrifugal fluidics in the chemistry and biological process such as separation science.

## ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI Grant-in Aid for Young Scientists (B) 23760150.

## REFERENCES

- [1] Ali Asgar S. Bhagat, Sathyakumar S. Kuntaegowdanahalli, Ian Papautsky, *Continuous particle separation in spiral microchannels using dean flows and differential migration*, Lab on a chip, 8, 1906-1914, (2008).
- [2] Ali Asgar S. Bhagat, Han Wei Hou, Leon D. Li, Chwee Teck Lim, Jongyoon Han, *Dean flow fractionation (DFF) isolation of circulating tumor cells (CTCs) from blood*, Proc. of Micro Total Analysis Systems 2011, 524-526, (2011).
- [3] Myung Gwon Lee, Chae Yun Bae, Sungyoung Choi, Hyun-Jung Cho, Je-Kyun Park, *High-throughput inertial separation of cancer cells from human whole blood in a contraction-expansion array microchannel*, Proc. of Micro Total analysis Systems 2011, 2065-2067, (2011).
- [4] Xiaole Mao, John Robert Waldeisen, Tony Jun Huang, *"Microfluidic drifting" -implementing three-dimensional hydrodynamic focusing with a single-layer planar microfluidic device*, Lab on a chip, 7, 1260-1262, (2007).
- [5] Jens Ducree, Thilo Brenner, Stefan Haeberle, Thomas Glatzel, Roland Zengerle, *Multilamination of flows in planar networks of rotating microchannels*, Microfluidics and Nanofluidics, 2, 78-84, (2006).
- [6] Jens Ducree, Stefan Haeberle, Thilo Brenner, Thomas Glatzel, Roland Zengerle, *Patterning of flow and mixing in rotating radial microchannels*, Microfluidics and Nanofluidics, 2, 97-105, (2006).
- [7] David C. Duffy, J. Cooper McDonald, Olivier J. A. Schueller, George M. Whitesides, *Rapid Prototyping of Microfluidic Systems in Poly(dimethylsiloxane)*, Analytical Chemistry, 70, 4974-4984, (1998).

## CONTACT

Yoshiaki Ukita +81-791-51-1663 or ukita@jaist.ac.jp

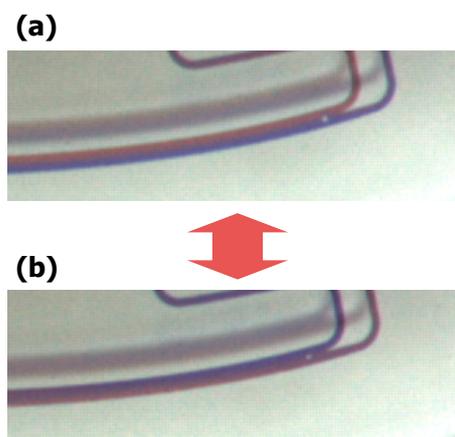


Figure 5. A result of flow switching demonstration. (a) Laminar flow separation mode (1000 rpm) (b) Secondary flow switching mode (3000 rpm).