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Particles Trajectories Simulation of Hydrodynamic Focusing in Circular and Rectangular Polymer Microflow Cytometer

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Abstract

Hydrodynamic focusing is an important method used in microfluidics cell sorting devices. It is a technique that allows two sheath fluids to conflow at different velocities to obtain the focusing of sample fluid. The objective of hydrodynamic focusing is to make sure the particle arrives one by one at detection source. Simulation is done using COMSOL Multyphysics software to observe particle trajectories in micro flow cytometer with circular and rectangular cross-section. The density and sizes of the particles is similar to protein particles properties. Normal inflow velocity fot sheath channel is 800µm/s and normal inflow velocity for sample channel is 150µm/s. At The beginning of the experiment, circular flow cytometer was expected to have better hydrodynamic focusing effect and better particle trajectories. However, after the simulation is done the results show that particle trajectories in rectangular channel are better. Reduce channel height is one of the factor that enables particle to focus in the middle of the channel for the rectangular shape channel device.

Keywords: COMSOL, Hydrodynamic focusing, Microflow cytometer, Microfluidics

BACKGROUND/ OBJECTIVES AND GOALS

This paper presents the simulation of particle tracing in both microfluidics channel with rectangular and circular cross-sections. Theoretically, circular shape is better shape of fluid flow mechanism(Selamat, Syafiq, Rahim, & Ehsan, 2016)(Lumpur, Rahim, Selamat, Yunas, & Ehsan, 2016). The focusing effect and particle tracing trajectories was studied and discussed.

INTRODUCTION

Flow cytometer is a technology in molecular biology to measure physical and chemical characteristics of a single particle that pass under detection source one by one. One of the major application of this device is for cell sorting and counting(Fu, Yang, Lin, Pan, & Lee, 2004)(Rosenauer & Buchegger, 2011)(Tung, Zhang, Lin, Kurabayashi, & Skerlos, 2004). Flow cytometry is a technique for counting and analyzing particles by suspending the particles in a stream of fluid and passing them through a detector. Basically, there are three main steps in flow cytometer: focusing, detecting, and sorting. In order to analyze the particle, the particles need to be focused at the center of the channel.

Hydrodynamic focusing is a technique that allows two sheath fluids to conflow at different velocities to obtain the focusing of sample fluid(Lee et al., 2001). Flow cytometer is a device whereby particles can be analyzed by using hydrodynamic focusing technique and then sorted based on the particle properties. This method allows the particles to arrive one by one therefore making detection process simpler. The width of the focusing stream is reduced in order to allow only one particle to stream at the center of the focused channel or stream. Hydrodynamic focusing is very important and it has been used in wide variety of application such as particle counting and sorting, microfluidic optical waveguides, fluorescent light sources and single-molecule detection and measurement(Wu & Hjort, 2009)(Teh, Lin, Hung, & Lee, 2008)(Barbulovic-Nad, Yang, Park, & Wheeler, 2008). Theoretically, neighboring sheath flows with higher velocity can hydrodynamically squeeze the sample flow into a single stream.

Rapid prototyping is where prototypes are design from a computer aided design CAD) and fabricate using automated fabrication process. It allows three dimensional (3D) objects to be fabricate from digital designs("Review on CNC-Rapid Prototyping," 2012)(Carlborg, Haraldsson, Oberg, Malkoch, & van der Wijngaart, 2011)(Raos, Stoić, & Lucić, 2005)(Vaezi, Seitz, & Yang, 2013). There are three major categories in the automated fabrication process: subtractive, additive and formative. Subtractive is a process where material is removed from a solid block of material until the desired object is obtained. While additive is a process of building up a design so that the material combine to produce desired design. Formative process is where mechanical forces are applied to the material so that the final design can be obtained.

The widely used rapid prototyping techniques for microfluidics devices are macro-machining, soft-lithography, embossing and injection moulding. However, most of these steps require multiple process and equipment and the device fabricated has limitation in terms of size and shape. Usually the channel fabricated will have rectangular cross section and it is very difficult to fabricate circular channel using machines. That is why we decided to use rapid prototyping (3D printer) to fabricate the circular channel

Recently, advancement in 3D printing can simplify the fabricaton process of microfluidics devices into one step(Nam, Yangfan, Yiwei, & Yin, 2015)(Considerations & Considerations, 2010)(Manuscript, 2015). This simulation is done for fundamental research of developing a 3D printed microfluidic device (flow cytometer). The 3D printer is liquid-based rapid prototyping (stereolithography).

Strereolithography is based on the application of a ultra violet (UV) laser which solidifies a liquid photopolymeric resin. The product is manufactured layer-by-layer by curing liquid resin. In projection stereolithography, the laser light source and scanner system are replaced with a liquid crystal display (LCD). Hence, each layer is cured at once in one exposure according to the pattern on LCD. The projection technique is based on digital light processing (DLP) projector which emits ultra-violet (UV) light which is required for curing the photopolymer .

METHOD

The device was simulated using COMSOL Multyphysics software. Three Dimensional simulations were used and the microfluidics module was selected. The physics that are involved in this simulation are the laminar flow and particle tracing for fluid flow. The simulation was done in both stationary studies and time –dependent studies mode. The objective is to observe the particle movement in both channels and which channel has better particle trajectories. Simulations were done in microfluidics channels with rectangular and circular cross sections. To have an equal comparison, the channel tested must have similar cross sectional area and length. A = 10000μm². The reason this area was chosen because of the limitation of micromachining fabrication.

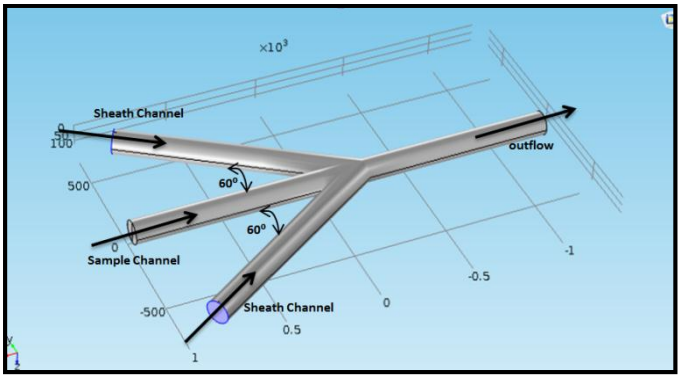

Figure 1: COMSOL module of flow cytometer.

Table 1: Dimension of rectangular channel

Cross-section	height, μm	width, μm	Inlet channels, μm	Focusing channel, μm
Rectangular	50	200	3000	3000

Table 2: Dimension of circular channel

Cross-section	height, μm	width, μm	Inlet channels, μm	Focusing channel, μm
Rectangular	50	200	3000	3000

Free tetrahedral mesh with extremely fine element was chosen and calibrated for fluid dynamics for both channels. Initially, normal mesh was selected for the mesh size but the result did not come out perfectly for rectangular channel. All other mesh sizes (extremely coarse, extra coarse, coarser, coarse, normal, fine, finer, extra fine) was selected until extremely fine is the only size that can generate the result perfectly for rectangular channel. But for circular channel, the result comes out perfectly even when using normal mesh. One of the reasons is because of the rectangular channel has smaller cross-section and it has to be meshed perfectly so that all the data can be read and simulated.

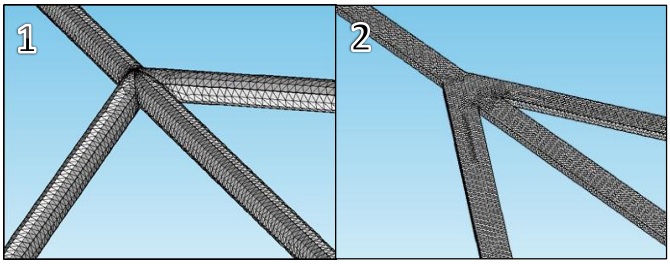

Figure 2: Geometry with free tetrahedral mesh

1) Free tetrahedral mesh for circular channel
2) Free tetrahedral mesh for rectangular channel

Table 3: Parameters and values used in COMSOL Multiphysics simulation

Particle density	Particle size	Normal inflow velocity (sample channel)	Normal inflow velocity (sheath channel)	Number of particle released
1540kg/m^3	1.5 nm	0.00015 m/s	0.0010 m/s	30

The density and sizes of the particles are similar to protein particles properties. Meanwhile, the inflow velocity for both sample and sheath channel were chosen based on the trials and simulations previously made before. If the inflow velocity is higher, the particle will move very fast and sometimes the particle move in cluster. In addition, if the inflow velocity is lower the particle will move very slowly and the focusing width will get affected. However, this parameter only valid if simulated using the same parameters design of both channels.

RESULTS

At time equals to 0s in picture (1, 2) in figure 3, particles were released into the channel and the velocity is high at the beginning. Meanwhile, at 5s and 10s (3, 4 in figure 2) particles started to move through the channel. Because of higher velocity in the middle of the channel, particles in the middle of channel move faster than particles near the channel wall.

At time equals to 15s, 20s and 25s in figure 4, particles are started to focus into one line. Even though the particles are moving in one line, because of the cross-section in circular channel, the particles are moving on top, middle and bottom of the channel. Interestingly for rectangular channel, particles

are moving only in the middle of the channel. It is because the rectangular channel has shorter width compare to circular still the particles in the middle move faster than particles near the channel wall

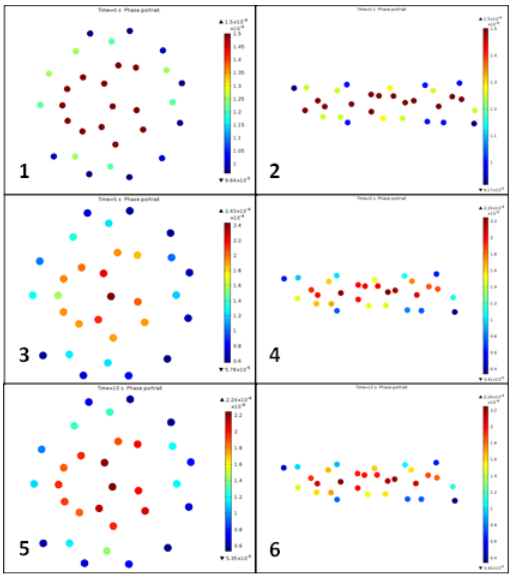

Figure 3: Image of phase portrait of the particles for circular channel and rectangular channel

3) Phase portrait image of circular channel when t = 0s
4) Phase portrait image of rectangular channel when t = 0s
5) Phase portrait image of circular channel when t = 5s
6) Phase portrait image of rectangular channel when t = 5s
7) Phase portrait image of circular channel when t = 10s
8) Phase portrait image of rectangular channel when t = 10s

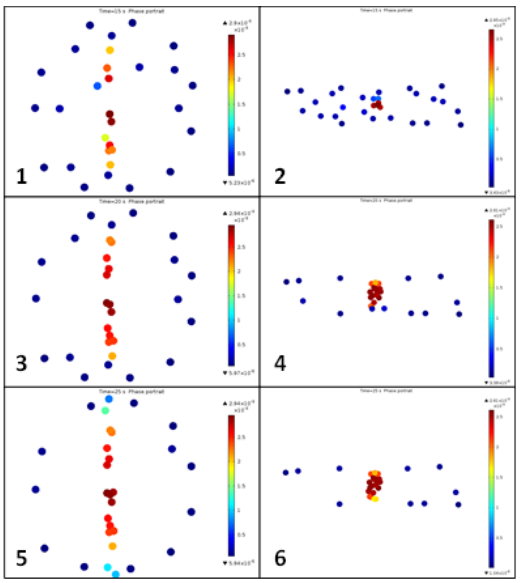

Figure 4: Image of phase portrait of the particles for circular channel and rectangular channel

9) Phase portrait image of circular channel when t = 15s
10) Phase portrait image of rectangular channel when t = 15s
11) Phase portrait image of circular channel when t = 20s
12) Phase portrait image of rectangular channel when t = 20s
13) Phase portrait image of circular channel when t = 25s
14) Phase portrait image of rectangular channel when t = 25s

At time equal to 30s, 35s and 40s in figure 5, most of the particles went through the channel and have been focused into one line, particles near the wall channel are moving very slowly and still have not reach the focusing area.

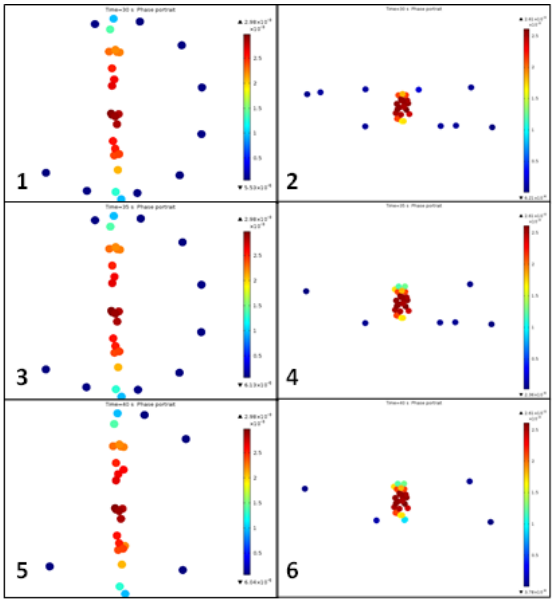

Figure 5: Image of phase portrait of the particles for circular channel and rectangular channel.

15) Phase portrait image of circular channel when t = 30s
16) Phase portrait image of rectangular channel when t = 30s
17) Phase portrait image of circular channel when t = 35s
18) Phase portrait image of rectangular channel when t = 35s
19) Phase portrait image of circular channel when t = 40s
20) Phase portrait image of rectangular channel when t = 40s

At 50s and 55 in figure 6, all the particles in the circular channel have reached the end of the channel. Meanwhile, there are still few particles are left behind in the rectangular channel possibly due to the high shear rate near the channel wall. Particles in the circular channel reach the channel outlet faster than particles in rectangular channel.

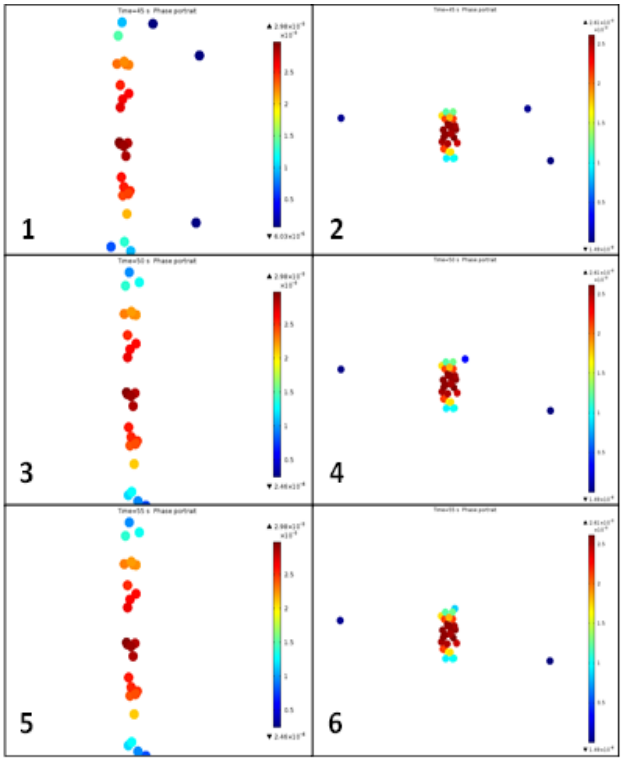

Figure 6: Image of phase portrait of the particles for circular channel and rectangular channel.

21) Phase portrait image of circular channel when t = 45s
22) Phase portrait image of rectangular channel when t = 45s
23) Phase portrait image of circular channel when t = 50s
24) Phase portrait image of rectangular channel when t = 50s
25) Phase portrait image of circular channel when t = 55s
26) Phase portrait image of rectangular channel when t = 55s

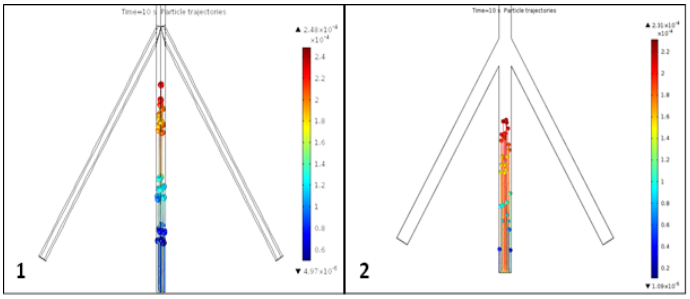

Figure 7: Particle trajectories for (1) circular channel (2) rectangular channel when time =10s

Figure 8 shows the time when the particles start to align for both circular and rectangular. For circular channel, particles start to align on 12.3s and for rectangular channel it is on 14s particle start to focus and align faster in circular channel.

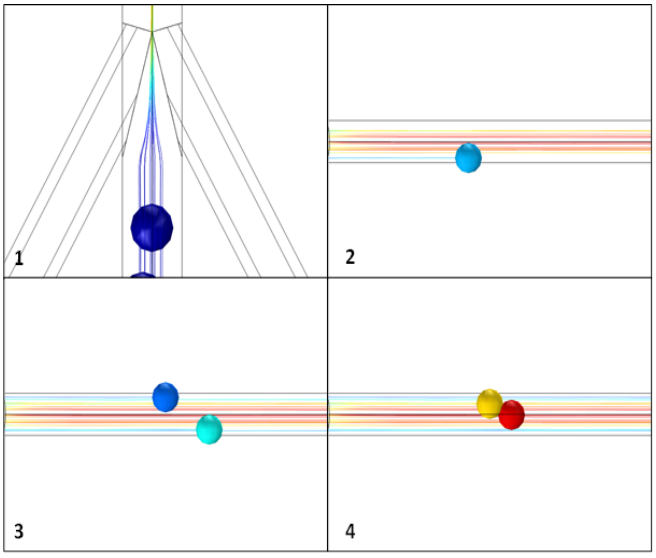

Figure 9: Particle trajectories for circular channel

For circular channel in figure 9, it can be seen that the particles can be focused into on single stream (1, 2). Unfortunately, due to the geometrical shape that has wider opening, the particles tend to move together through up and bottom of the channel (3). Sometimes the particles also move in group when the velocity is higher (4).

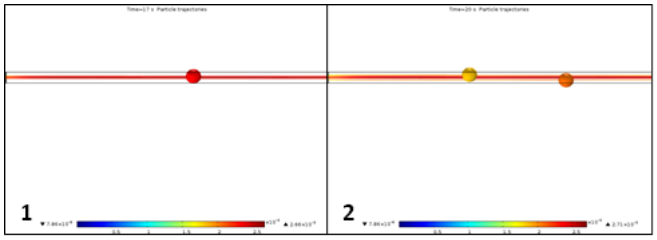

Figure 10: Particle trajectories for circular channel

In rectangular all particles are aligned in a single stream. Due to the shorter channel height compare to circular channel, particle only moves in the middle of the channel. So in this channel, particle can arrive one by one on detection source (2).

From the simulation result, rectangular channel gives better particle trajectories. It is because of the cross sections of rectangular channel, where it has a shorter length (smaller cross section), therefore the particle that has smaller sizes (nano size) can be aligned to the centerline of the channel and pass one by one. Meanwhile, the circular channel that has a wider cross section because of its diameter consequently allows the particles to be aligned to the centerline but it did not pass one by one. The particles are also moving at the top and bottom of the channel due to its small sizes. For instant like in the picture no 3 and 4 in figure 8.

CONCLUSION

Particles trajectories have been simulated in both circular and rectangular channel. The result shows that particle trajectories are better in rectangular channel since the particle manage to align and move one by one. In circular channel, the particles are tend to move in cluster or sometimes move together through up and bottom of the channel. It will make the detection process harder. At the beginning of the experiment, expectations are different since from the theoretical aspect circular channel is the best shape for fluid flow mechanism. However when particles are involved, hydrodynamic focusing is better in rectangular channel.

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