A novel design of bioinspired retinal vascular network based microchannel for LOC applications

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Abstract. Microchannels are identified as important components that transfer liquids within a minute area for microfluidic applications. Pressure controlling is an efficient and most accurate way to introduce a certain velocity of equipment. In this study, we described the simulation analysis for microfluidic channels with three inlets and one outlet and went on to optimize it to two inlets and one outlet with appropriate velocity profiles and pressure profiles. The grooves in the microchannel draw inspiration from the vascular network of the retina which is a dynamically interconnected structure composed of three planar vascular layers with bends and grooves at its tip ends. Different fluids enter the inlets and are supposed to get mixed as much as possible before leaving the outlet. The geometry needs to be modified to increase the mixing of the two fluids within 0.05 sec. A passive approach to induce mixing of the biological samples is facilitated by increasing the distances. The fluids travel longer distances for mixing because of diffusive and inertial forces for which the volumetric fluids travel long before mixing takes place. The channel length is increased by introducing groove along the center of each channel to increase the length for the mixing.

Keywords: Microchannel, Modelling, Simulation, Velocity, Pressure, COMSOL Multiphysics

1. Introduction

Microfluidic devices are a desirable platforms for a LOC device and is a result of extensive research all around the world. The capabilities of a typical LOC include reduced size, low chip fabrication cost, smaller sampling requirements, high surface to volumetric ratio and unprecedented control of energy and mass transport. However, mixing the fluids at smaller volumes is of greater importance for subsequent processing to develop an integrated LOC device as the existing units are expensive and much larger in size for a handheld device. Devices with smaller dimensions compared to their e particles flowing through it allow for efficient flow analysis and manipulation. Based on the criteria of separation of the flowing particles and its application, particles are mixed and dispensed into optimized and manipulated network paths or reservoir for the predetermined collection of samples for further analysis. Development of micro-
channels and its flow analysis using electro kinetic flow is analyzed. The concept of electro kinetic flow offers two main advantages [1]. The velocity profile of the developed devices is similar to its plug and play concept and mode which allows a simpler and optimum prediction of particle velocities with high speed flow switching for dynamic particle separation. By varying the focusing channel area, the electric potential and flow field of the buffer solutions changes in the mixing channels. In the concept of cell sorting, the design utilizes a cross shape, unity ratio for area of focusing channel to area of sample channel in a way to confine the stream of the sample. There are various methods to drastically minimize the effects of flow driven by pressure that include incremental variation in channel length, decrementing radius and varying the hydraulic resistance in the channel network. Increasing the hydraulic resistance is dominant because the channel length enlargement mitigates the advantages for the micro-devices to offer and reduce the meniscus radius to incorporate for fixed reservoirs. The micro-channel is designed with three inlets and an outlet as the FEA analysis shows laminar flow characteristics operating at a volumetric flow rate in between 0.5 to 1000 µL/min. The pressure drop across the micro-channel in determining the limit for a micro-channel. The fluid mixing by micro-channels have a Reynolds number and a high Peclet number.

The large difference between the diffusive forces and inertial forces include the mechanism to travel very long distances for the analytes to get dispersed [2]. Long travel distances here include few centimeter for the fluid to travel. There are two possible ways to overcome these constraints, one by applying external input of energy to agitate the microfluidic flow which supposed to be laminar in nature in the form of turbulence which is an active approach. In the work, passive strategy is adopted to induce mixing. Microchannel design optimization: The figure 1 shows a micro-channel with three inlets and an outlet. The flow in a microchannel occurring in narrow channels of smaller dimensions of the range 20-50 um is a basic component of a microfluidic LOC device.[3] A detailed understanding of the thermal physics of such flows is an important aspect of the design, modelling and fabrication of LOC devices.[4]-[9]. The fluid flow manipulation in a microchannel or infuser is one of the important parameter for analysis. Along with the function of delivering the reactants, a physical particle separation, chemical mixing and computer chip cooling are provided by an efficient microchannel that forms the core of a LOC component.

Vorticity is generated inside droplets due to velocity distribution and immiscible condition: fluid elements in the center are moving faster than those near channel walls; circulating occurs since the fluid elements in
the center are forced to move back because they cannot penetrate the fluid interface. Fluid flows are described by the Navier–Stokes (N-S) equation, which is a set of partial differential equations with time and space dimensions.[10-11] The idea of CFD simulations is to obtain the flow field inside those microfluidic devices by solving the N-S equation through numerical methods. Conventional numerical methods include FDM (Finite difference method), FVM (Finite volume method) and FEM (Finite element method). Many commercial CFD software or packages are available viz. ANSYS Fluent, ANSYS CFX and COMSOL Multiphysics. Open source numerical solvers such as Open Foam, Fluent and Open Foam are based on FVM while COMSOL and CFX adopt FEM methods. This paper seeks to apply CFD simulations to understand the flow behavior inside microfluidic reactors to find suitable operating conditions and optimal designs for nanoparticle synthesis. The flows manipulated in laminar regime with Re<1 and both the fluids modelled as incompressible Newtonian fluids. Only a single set of continuity equation and momentum equation was solved continuously throughout the computational domain.

A microchannel is designed, a device that feeds a reactor with a specified volume of fluid through it. Pressure controlling will set the volume of fluid at a specific velocity. The time-domain modelling for a microchannel inlet pressure reduces the pressure. Therefore, the model demonstrates the usage of the tool COMSOL Multiphysics to solve the various time-dependent boundary conditions and sweep meshes into 3D to allocate appropriate memory data.

2. Design of Vascular Network

2.1 Functional aspect of a vascular network

The retinal vasculature is a capillary network of blood vessels that nourishes the inner retina of most mammals as shown in figure.2. The retinal vascular network of mammals constitutes the network of capillary tubes in a densely interconnected pattern of veins with very small dimensions for the circulation and regulation of oxygen and nutrients to the retina. A biomimetic inspired array or network of the vascular domain of the retina as microchannels for a LOC application is attempted and simulated as shown in figure.3. From the perspective of the functioning of the vascular capillary network, its functioning is a real challenge and biomaterials for the artificial network is regressively under study by the researchers all over. Various approaches have been developed in the past pertaining to the challenge posed that includes (i). the incorporation of biomolecular cues within the materials (ii). Seeding methods of vascular inducing cells (iii). Use of miniaturization technologies to engineer the branched microfluidic channel within the biocompatible material. Hereafter, careful study of the retinal vascular network and its functioning, the structure is incorporated into our design and simulated using FEA analysis tools i.e COMSOL Multiphysics.
2.2 Model Design of microchannel

The flow of fluid with specific volume flow through a microchannel with a number of characteristic features for laminar flow. The domain velocity profile of the flow has unique parabolic shape with increasing velocity at the center of the channel and decreases towards the vertical wall of channel as shown in figure 4. The motion of particles in the laminar flow is orderly arranged with particles close to a solid surface moving in a straight path parallel to the surface.

The biomimetic model designed with 3 inlets and 1 outlet whose velocity as depicted from the simulation suggests laminar flow. In the design, the bioinspired vascular network is incorporated with the construction of geometry as the number of microchannels limiting to 3 with a V-groove as observed and modelled in the retinal vascular network. The number of channels can be increased based on the application of the LOC and the number of buffer solutions required with different inlets. The differential pressure at the inlet and outlet is time-domain controlled so that the fluid flows smoothly from inlet to outlet. At an instant of time inlet flow dominates the outlet flow, it could be beneficiary from more than one inlet. Figure 5. shows the V-groove shaped infuser with the biomimetic vascular network. The model sets up a differential pressure difference at each inlet in the time domain such that the inlets pressure dominates the outlet.
This implies that the numerical solution using COMSOL for a full momentum balance and the continuity equations for the flow of the incompressible fluid for a significant number of elements is advantageous. The time-domain equations of Navier-Stokes are used as a base. Each subsection of the microchannel arrangement is shown in figure.3 with V- groove-shaped infuser for the simulation of a retinal based microchannel. Here the concept of biomimicry arises as the ends of the retinal network are depicted with the prescribed grooves. Semiautomatic and automatic various meshing tools in COMSOL Multiphysics include tetrahedral in a free mode and sweep. The default and efficient algorithm in the toolbox is tetrahedral for solids and a combination of tetrahedral and boundary layer meshing for compressible fluids. A mesh sequence is defined and created with the process allowing for the mix of prismatic, tetrahedral and can be parametrically driven.

3. Results of the Simulation and Analysis

3.1 Velocity profiles of the designed microchannel

The drop in pressure during the fluid flow for the designed V-groove shaped microchannel exhibits a maximum pressure of 57.6 Pa and a minimum of 2.2 Pa. The minimum pressure is at the outlet compares to the three inlet pressures. The pressure profiles as shown in figure 4. conclude that the dimensions of the channel in specific the optimized dimensions are fine at the inlets of the top and the bottom but not the left-most pressure. That implies that the pressure is insignificant at the right- inlet and does not contribute effectively to the microchannel structure, a lot of diffusive force is required to push the liquid towards the other two inlets and hence towards the outlet for the design. This is overcome by eliminating the right inlet and allowing the mixing of fluids from the topand the bottom inlet channels. The profile velocity fields with a combined slice and an arrow plot option through the center of the geometry at time t=0.5s.

![Figure 4](image_url)

**Figure 4.** (a) Contour pressure of the inlet and outlet valves of the designed microchannel. (b) Velocity magnitude and field plots of the infuser of a microchannel

The velocity magnitude at the left inlet channel is almost 0 mm/s and for the top, it turns to be in the range of 4 mm/s to 5 mm/s whereas for the outlet channel it is the maximum with a value of 7.5 mm/s. In further analysis, selection of domain vertices for velocity magnitude as the time elapses for pressure profiles. The plot of the four points along the inner entry of each channel is shown in figure 4 and explains the distribution of the velocity of the fluid that is flowing within a time span of 0.5 s.
For the outlet entry point, the velocity magnitudes are higher with a time span of 0.5 s to a value of 55 m/s. And for the topmost and the bottom-most, the values of the velocity are 50 m/s. Density for the outlet channel is 1000 kg/m3 from the simulated results with a shear rate of 1.5 /s throughout the structure. The dynamic viscosity for the structure of the microchannel is 0.001 Pa-s with an acceleration magnitude of 1 m2/s. The velocity profile indicates a pressure velocity of 7.5 to 8 Pa at the inlet valves in the X direction and pressure of 7 to 8 Pa at a point near the output with respect to time. Error rate decreases as the iteration number increases as shown in figure.5. The error rate is within the specified limits decreasing to 10e-7 for 4th iteration.

![Figure 5](image)

**Figure 5.** (a) Contour velocity magnitude.(b) Pressure contour with streamlines x-z plane.

Three dimension plots to visualize the fluid in the micro channel is performed. The isosurface plots reveal that there is an obstruction for the fluid for its flow in both the directions and hence not a favorable design for the microchannel. Here the period for which the analysis is performed is 4s. The outlet channel exhibits the maximum velocity in terms of both isosurfaces and also contour. In the next plot slicing is performed choosing the x-z plane as the intersection and the number of planes chosen for analysis is 35. As from the plot, it is observed that contour pressure at the topmost inlet channel is maximum when compared to the bottom-most and the rightmost. The values for the contour pressure at the top inlet channel is $3\times10^{-3}$ Pa and 6 mPa for the outlet channel.

### 3.2 Design 2 of microchannel

The optimization of design 1 analysis shows that the right inlet offers very low pressure and velocity for the fluid to diffuse into the further channels for analysis and henceforth can be avoided in the design. The figure 6 show the plots of the optimized two inlet and one outlet microchannel and retaining the V-groove as in the design 1. The top inlet exhibits a maximum velocity of 4 m/s and minimum of 2 m/s. the bottom inlet for the microchannel exhibits 5 m/s and a minimum of 1 m/s. The arrows indicate the direction of flow of the fluid through the microchannel. As in the Figure.6, we have sliced the isosurfaces of the microchannel along the x-z direction and the velocity magnitude is 8.95 m/s. Their maximum contours occur the center of the outlet channel 8.59 e-3 with contour values of 0.22 e-3 at the boundaries of the microchannel inlets.
Figure 6. (a) Velocity field of Design 2. (b) Streamline pressure plots sliced along the x-z plane

Further analysis is carried out with streamline plots as shown in Figure 7 with sliced planes of 5 along x-z direction. Here the pressure profiles are very high to a maximum of 58.5 Pa at the inlets i.e top and bottom. The iso surface plot shows the path of fluid flow inside the microchannel eliminating the boundaries. This verifies that the optimized design 2 is optimum for the V-groove biomimetic inspired microchannel.

Figure 7. (a) Detailed analysis of V-groove microchannel. (b) Velocity profile of a typical inlet of a microchannel

Here a detailed analysis is carried separately for the inlet and then for the outlet. So for the inlet, the pressure profiles show that the boundaries exhibit the maximum pressure than the V-groove which we have introduced 8 mPa is the pressure at the inlet and 6 mPa is the pressure at the V-groove junction. Similarly, we can analyze the slice along the x-z direction at the outlet. We can differentiate that different layers in the outlet exhibit different pressure and hence different velocity. There is very low pressure of 0.5 mPa at the boundaries of the outlet and 8 mPa at the center. Here y-shear at the walls insignificantly due to the flow through the channel, the velocity as a function of x in a fully functioned regime. This induces a velocity gradient in the y-direction although negligible as compared to the x-shear. The existence of the dominant y-shear can be shown by introducing a radial velocity into the microchannel.

4. Conclusion
A bioinspired V-groove microchannel from the designed mimicked from the retinal vascular membrane of the eye. Here the number of inlets is limited to three for the simulation in COMSOL Multiphysics and can
be further increased to a value of 10 maximum based on the number of buffer solutions used and the interacting solutions required for the analysis in the microreactor. This design also facilitates the mixing of the fluids at the V-groove for each of the inlet and outlet valves. The mechanism and the structure are designed in an appropriate way mimicking the naturally existing vascular network which in turn is a complex network. The top and the bottom inlets perpendicular to each other are offering the fluid the required fluid velocity and the pressure difference to travel and mix in the microchannel with a maximum and minimum values of 57.6 and 2.2 respectively.

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