Numerical Modeling of Flow through the Vertical Rectangular Microchannel for Drug Screening Applications

Kalpana Seelam¹, Dr. A. Daisy Rani ²

¹Department of Instrument Technology Andhra University, Visakhapatnam
²Dept. of Electronics & Instrumentation Engineering, V.R. Siddhartha Engineering College, Vijayawada

e-mail: ¹kalapanaseelam@gmail.com, ²adaisyrani.inst@auvsp.edu.in

Abstract. A numerical study of flow in the rectangular vertical microchannel for drug screening applications is described. The flow characteristics through the microchannel are presented by incompressible Naiver-Stoke equations. Flow rate is evaluated from numerical modeling to simulate the drug flow through the microchannel. Here in this study, computational fluid dynamics based finite element method commercial software COMSOL is used for simulation of drug flow through the artery for cancer drug screening applications. The simulation work also presents the diffusion velocity at the intersection area between the drug and cancer cells.

Keywords: vertical rectangular microchannel, Naiver-Stokes equations, Drug flow, drug screening, diffusion velocity.

1. Introduction

The flow through the microchannel has been given great importance in recent years due to its new applications in microfluidic devices such as drug delivery, cell modeling, analyzing DNA, cell and drug screening [1]. Microchannel is integrates with microsystems in different applications, for example, miniature heat sink, miniature biosensors, reactors and miniature measured needles [2-4], so it is imperative to know the liquid stream qualities through miniature channel for better plan of different miniature fluidic applications. The advances in fabrication process increase the interest in study of flow through different shapes such as rectangular, circular, triangular, trapezoidal and circular. In many applications rectangular and trapezoidal shapes have been studied for microfluidic applications because of practical issues in fabrication techniques and cost [5-6]. In this work drug flow through the microchannel in vertical parallel plates were considered.

In chemotherapy treatment each patient required different drugs or combination of two or three drugs to treat the tumor because the drug efficiency depends on the genetic conditions of the patients. In olden days image based technologies such as MRI and CT scan are used to evaluate response of tumor to the anticancer drugs based on the parameter called tumor size. Slowly this method is converted into static drug screening method it gives better results than the image based drug screening.
In order to monitor the efficiency of the drug it takes more than three weeks. It is the main challenge in drug screening for cancer applications because timely management is one most important point the cancer treatment [7-8]. Microfluidic based biosensors plays very vital role in future for in-vitro cancer modules due to their ability of modifying the cell behavior at the individual level [9]. Animal studies for drug screening gives wrong analysis because they don’t have human host cell structure, where as in the microfluidic bio-sensor, the screening process can be directly done on the tissues collected from patient by using biopsy process [10]. Flow rate through the micro channel may create shear stress on the tissue so optimal flow rate should select to reduce the stress on the cells [11-12].

2. Mathematical formulation of model.

The drug flow was considered as
a. Incompressible
b. steady, and parallel
c. The flow has very low Reynolds number that is flow is laminar and viscous fluid falling between two vertical plates of gap h.
d. The pressure throughout the flow is constant.

e. Fluid flows by gravity alone no external force acting on the fluid.
f. gravity acts in the negative Z direction

The following assumptions are taken while solving flow characteristics through the microchannel

in x, y and z the velocity components are I, j and k respectively.
1. The fluid flow through the micro channel is Newtonian and incompressible
2. The plates are infinite in the (y-z) plane (y is into the board)
3. The flow through the micro channel is parallel (x-component of velocity ,i is zero)
4. Applied pressure gradient is zero.
5. The velocity field through the microchannel is purely two-dimensional, which implies that j = 0 and all partial derivatives of y are equal to zero.
6. \( g_z = -g \)
7. The flow through the microchannel is steady,
   i.e. \( \frac{\partial}{\partial t} = 0 \)
8. No slip boundary conditions at the walls

![Figure 1: Fluid flow through the microchannel](image-url)
Continuity equation in Cartesian coordinate system
\[ \frac{\partial i}{\partial x} + \frac{\partial j}{\partial y} + \frac{\partial k}{\partial z} = 0 \]
\[ \frac{\partial i}{\partial x} = 0 \quad \text{Assumption 3} \]
\[ \frac{\partial j}{\partial y} = 0 \quad \text{Assumption 5} \]
\[ \frac{\partial k}{\partial z} = 0 \quad \text{Continuity} \]

Assumption 7
[85x610] \[ \frac{\partial k}{\partial t} = 0 \quad \frac{\partial k}{\partial x} = 0 \quad \frac{\partial k}{\partial y} = 0 \quad \text{Assumption 4} \]
[85x622] \[ \rho \frac{\partial^2 k}{\partial z^2} = -\rho g \quad \text{Flow is in } -z \text{ direction} \]

From (2) we can write (3) as
\[ \frac{d^2 k}{dx^2} = \frac{\rho g}{\mu} \quad \text{--------}(4) \]

Solve the equation (4) to get velocity
\[ k = \frac{\rho g}{2\mu} x^2 + a1x + a2 \quad \text{--------}(5) \]

From wall boundary condition (1)
\[ 0 = \frac{\rho g}{\mu} h^2 - \frac{a1h}{2} + a2 \quad \text{--------}(6) \]

And wall boundary condition (2)
\[ 0 = \frac{\rho g}{8\mu} h^2 + a_1 \frac{h}{z} + a_2 \quad \text{----------(7)} \]

Solve the equations 6 and 7 to get \( a_1 \) and \( a_2 \)
\[ a_1 = 0, \quad a_2 = \frac{-\rho g h^2}{8\mu} \]

Substitute above constant values in equation 4 to get
\[
\text{Velocity} \quad k = \frac{\rho g}{2\mu} \left( x^2 - \left( \frac{h}{z} \right)^2 \right)
\]

Where \( \rho \) is density of the fluid, 
\( \mu \) is dynamic viscosity of the fluid, 
\( g \) gravitational constant 
\( h \) is width of the channel.

3. Simulation Of Proposed System

In drug screening applications transport mechanism is very important. Different methods are available to transport the drug like pressure-driven methods and so on. Diffusion is the primary method for drug transport in-vivo among vessels and cells. By simulating the model we can observe the diffusion velocity at the interaction area of the drug and the cells. Figure 2 shows the model configuration in that width of the channel is 650µm which is near to the pulmonary vessel’s upper diameter [13].

![Figure 2. Block diagram of microfluidic platform for drug Screening](image)

Figure 2 shows the block diagram of the proposed system, in that gel loaded with cell are placed in chamber, the drug flows through the microchannel and interact with the cells at the intersection area. In order to provide the interaction between cancer cells and drug a slit of 0.25mm is given. Our numerical modeling showed that 0.06µL/sec flow rate which satisfies the interstitial flow criterion. By using COMSOL5.2 software we simulated the proposed model for diffusion velocity at the interaction area for the flow rate 0.6 µL/sec.

4. Results

For non-metastatic cancers in-vivo environment the interstitial flow is between 0.1 µm/s - 1µm/s [14-15]. The above numerical modeling shows that the flow rate through the microchannel is 0.06
L/sec. The flow through the micro channel is set as creeping flow and flow properties are solved by Naiver-Stokes and continuity equations.

![Image: Velocity plot in Microchannel]

The current design of the microchannel, the rate of flow 0.06 μL/sec offers the flow rate of 0.99μm/sec at the interaction space that is within the range of interstitial flow for cancer [15]. Figure 3 shows the simulation results of flow through the microchannel.

5. Conclusion
We presented numerical modelling of velocity of flow through the vertical rectangular microchannel for drug screening applications by using Naiver-Stokes equations and also presented diffusion velocity at the interaction area. Further we can work for optimization of flow through the microchannel for cancer drug screening applications.

6. Acknowledgement
Kalpana seelam acknowledge the Depertment of EIE in Velagapudi Ramakrishna Siddhartha Engineering College Vijayawada and Andhra University, Visakapatnam, Andhrapradesh for providing facilities to complete the manuscript.

Conflict of interest: S.Kalpana, Dr.Daisy Rani Ali declare that they have no conflict of interest.

References
[1] George M. Whitesides, 2006, The origins and the future of microfluidics, Nature 442, 368-372.
[2] Sergey V. Ermakov, Stephen C. Jacobson, and J. Michael Ramsey, 1998, Computer Simulations of Electrokinetic Transport in Microfabricated Channel Structures. Analytical Chemistry 70 (21), 4494-4504.
[3] Yuanhai Su, Yang SongLiang, Xiang. 2020, Continuous-Flow Microreactors for Polymer Synthesis: Engineering Principles and Applications, Accounts on Sustainable Flow Chemistry,147-190.
[4] DeWitt, S., 1999, Microreactors for chemical synthesis, Combinational Chemistry 3, 350-356.
Ryo Miyake, Theo S. J. Lammerinkz, Miko Elwenspoek, Jan H. J. Fluitman, 1993, Micro Mixer with Fast Diffusion, IEEE proceedings MicroelectroMechanical systems, 0957-2193.

[5] Bayraktar, T., Pidugu, S.B., 2006, Characterization of liquid flows in microfluidic systems, Int. J. of Heat and Mass Transfer 49, 815-824.

[6] EK Sackmann, AL Fulton, DJ Beebe, 2014, The present and future role of microfluidics in biomedical research, Nature 507,181-187.

[7] Squires, T.M., Quake, S.R., 2005, Microfluidics: fluid physics at nanoliter scale, Review of modern physics 77, 977-1026.

[8] Zlatos A., Diffusion in fluid flow: Dissipation enhancement by flows in 2D. Communications in Partial Differential Equations, 2010, (35)3, 496-534.

[9] Calleja A.B., Li R., Chen M.B., Wong S.C., and Kamm R.D., Microfluidics: A New Tool for Modeling Cancer–Immune Interactions Trends in Cancer, Trends Cancer, 2016, 2(1), 6-19.

[10] Ling Z.-Q., Qi C.-J., Lu X.-X. et al., Heterogeneity of chemosensitivity in esophageal cancer using ATP-tumor chemosensitivity assay, Acta Pharmacol Sin., 2012, 33(3), 401–406.

[11] Tehranirokh M., Kouzani A.Z., Francis P.S., and Kanwar J.R., Microfluidic devices for cell cultivation and proliferation, Biomicrofluidics, 2013, 7, 051502.

[12] Cavallotti C., D’Andrea V., Cavallotti C., Cameroni M., Distribution of acetylcholinesterase and cholineacetyl-transferase activities in the human pulmonary vessels of younger and older adults, Geriatr Gerontol Int., 2005, 5, 286–292.

[13] Tarbell J. M., Shi Z. D., Effect of the glycocalyx layer on transmission of interstitial flow shear stress to embedded cells, Biomech. Model. Mech. Biol. 2012, 12, 111–121.

[14] Hompland T., Ellingsen C., Øvrebø K. M., Rofstad E.K., Interstitial fluid pressure and associated lymph node metastasis revealed in tumors by dynamic contrast-enhanced MRI, Cancer Res. 2012, 72(19), 4899–4908.

[15] Natarajan, B., Obaidat, M.S., Sadoun, B., Manoharan, R., Ramachandran, S. and Velusamy, N., 2020. New Clustering-Based Semantic Service Selection and User Preferential Model. IEEE Systems Journal. DOI: 10.1109/JSYST.2020.3025407.

[16] Nataraj, S.K., Al-Turjman, F., Adom, A.H., Sitharthan, R., Rajesh, M. and Kumar, R., 2020. Intelligent Robotic Chair with Thought Control and Communication Aid Using Higher Order Spectra Band Features. IEEE Sensors Journal, DOI: 10.1109/JSEN.2020.3020971.

[17] Babu, R.G., Obaidat, M.S., Amudha, V., Manoharan, R. and Sitharthan, R., 2020. Comparative analysis of distributive linear and non-linear optimised spectrum sensing clustering techniques in cognitive radio network systems. IET Networks, DOI: 10.1049/iet-net.2020.0122.

[18] Sitharthan, R., Yuvaraj, S., Padmanabhan, S., Holm-Nielsen, J.B., Sujith, M., Rajesh, M., Prabaharan, N. and Vengatesan, K., 2021. Piezoelectric energy harvester converting wind aerodynamic energy into electrical energy for microelectronic application. IET Renewable Power Generation, DOI: 10.1049/rpg.2.12119.

[19] Sitharthan, R., Sujatha Krishnamoorthy, Padmanaban Sanjeevikumar, Jens Bo Holm-Nielsen, R. Raja Singh, and M. Rajesh. "Torque ripple minimization of PMSM using an adaptive Elman neural network-controlled feedback linearization-based direct torque control strategy." International Transactions on Electrical Energy Systems 31, no. 1 (2021): e12685. DOI: 10.1002/2050-7038.12685.