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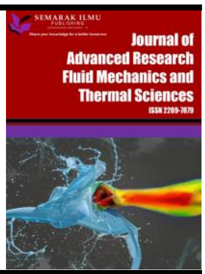

The Characterisation of Differential Pressure Based Flow Sensor in a Microfluidic Environment

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ABSTRACT

Flows in a microfluidic environment differ in their flow parameter changes compared to macro flows and should be handled carefully. Recently microfluidic innovations have been drawn into much consideration in biomedical, chemical synthesis, and cooling industries. There exists a need for a flow rate sensor for measuring tiny fluid flows in developing microfluidic Lab-on-chip products, Organ-on-chip, and other products for biological, chemical, and other flow analysis. Working with microfluidic products mainly revolves around flow measurement. The control of these frameworks is just conceivable with sensors that estimate flow rate. In this work, we understand the dynamics of microfluidic flow and try to determine its influence on sensor behavior. The paper presents the construction of flow-sensing techniques for microflows. The design of the microchannel opted for the study is also discussed. A microfluidic flow rate sensing technique is put forward using the physical principle of fluid dynamics; based on pressure in a rectangular microchannel. For rectangular microchannel, the variation in pressure had an impact on the flow rate measurement of the microflow sensor.

1. Introduction

In the past three decades, fluid flow has been applied in producing industrial products like pharmaceuticals [1] and cosmetics. Power generation using water flow [2], water supply, water treatment, and sewage management are the few other sectors that employ fluid flows. Among the various fluid flows, the microfluid flow has been discussed more in the past decade regarding technology that facilitates humankind in terms of biological and chemical aspects [3]. The microfluidics field deals with the microflows of various fluids [4] and has risen to a new zone of exploration with its use in different interdisciplinary areas [5]. Microfluidics is the innovation of fluid control in different pathways [6] with measurements of several micrometers. This field offers a developing arrangement of tools for controlling small volumes of liquids and manipulating chemical, biological [7], and physical characteristics of microfluid flow. Currently, microfluidics is performing great in medical [8], blending [9], sorting [10], cooling [11], and heat transfer areas [12,13].

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Variation in microfluid flow instances causes variation in its related variables in the microfluid flow process [14]. Recently, new biological and chemical synthesis challenges are arising, leading to the need for more sophisticated microfluidic products [15]. Such demands result in microfluidic innovations for investigating microfluid flow parameters. The need in microfluidic applications to analyze and manipulate has leaped novel exploration of measurement tools for flow parameter monitoring [16].

The paper here concentrates on parameter variations in microflows and their effect on the sensor. Flow rate is one of the critical characteristics of microfluid flows, whose variation strongly dictates the balance and stability of the microflow environment. Also, the monitored variations in micro flow rate are potentially being used to form applications like blending, sorting, and cooling. In this regard, there is a need for microflow sensor inventions now and then to the demands of microfluidic applications environments. The present study generates a flow rate sensing hypothesis using basic fluid flow principles for single-phase liquid flow and rectangular microchannel.

2. Formulation and Methodology

Applications in microfluidics depend on the microflow parameter measurement and microchannel geometry. Microflow parameters can be measured for different microchannels with different microchannel geometry parameters like circular, square, triangular, rectangular, cylindrical, and serpentine designs. Microflow parameter measurement in these microchannel designs is vital to facilitate the performance of any microflow systems. Moreover, sensing microfluidic flow parameters depends on the basic principles of fluid dynamics at the microscale.

2.1 Flow Sensor

A flow sensor is important in monitoring and controlling flow in any fluid flow environment for the flow system to remain stable. Flow sensors play a critical role in monitoring fluids in microfluidic systems. The principle of any microfluidic flow sensor depends on the basic principles of fluid dynamics. Pressure is one of the microfluid flow parameters that can be used to calculate flow rate according to Hagen–Poiseuille law [17]. Hence Hagen–Poiseuille law forms the basis for the flow rate calculations through pressure variations of fluid flows in microfluidic environments.

2.2 Microchannel Design

Much work is done on cooling applications in the microfluidic field. A rectangular microchannel is preferred in cooling applications like microelectronic or refrigeration processes. Hence, among many microchannel designs and orientations, a model with straight-oriented rectangular microchannel with a constant depth is chosen for the present study. Figure1, Figure 2, and Figure 3 are top view, longitudinal, and cross-sectional views of a planned microfluidic chip with a microchannel, respectively. Microchannel is here considered for single-phase liquid transport. Draft Angle connects with how vertical the microchannel barriers are. For the exact vertical wall, there is no draft. The draft angle is considered zero in the plan, and thus no adjustment factor is incorporated.

Fig. 1. Microfluidic chip top view (Green-microchannel, Red-ports)

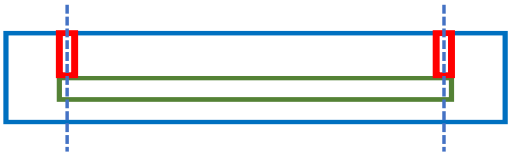

Fig. 2. Longitudinal view of microfluidic chip with constant depth microchannel

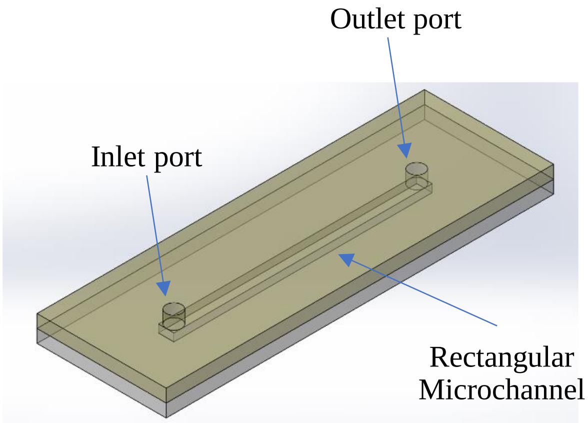

Fig. 3. Cross-sectional view of microfluidic chip with rectangular miniature channel

2.3 Working Principle for Rectangular Microchannel

Pressure drop and flow rate are the microflow parameters considered for this study. A rectangular microchannel with an inlet and outlet is considered as in Figure 4. As per Hagen–Poiseuille, the pressure drop between two extremities in the microchannel is given by Eq. (1) [18].

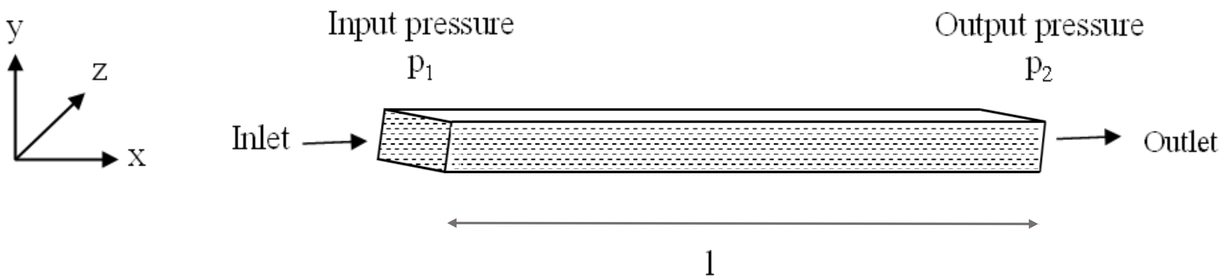

Fig. 4. Microchannel Diagram

$$\Delta p = (p_1 - p_2) = \frac{aQ\mu l}{nm^3} \tag{1}$$

$$Q = \frac{nm^3 \Delta p}{a\mu l} \tag{2}$$

$$a = 12\left[1 - \frac{192m}{\pi^5 n}\tanh\left(\frac{\pi n}{2m}\right)\right]^{-1} \tag{3}$$

where, p_1 and p_2 → pressure at entry and exit of the microchannel, Q → mean volumetric flow rate, m and n → height and width of the microchannel, μ → liquid viscosity, l → gap in the middle of two extremities over where the pressure drop occurs, and a → fixed value particular to microchannel geometry and can be determined by Eq. (3) [18].

The input velocity for the setup shown in Figure 1 is varied, which in turn changes pressure. Depending on the pressure drop across the entry and exit of the microchannel, the flow rate is calculated using Eq. (2) [18].

A completely evolved laminar stream can be acquired after a distance given by Eq. (4) [19]. Eq. (5) and Eq. (6) give Reynolds number and hydraulic diameter, respectively [19]

$$l_e = d_h\left(\frac{0.6}{1+0.035r_e} + 0.056r_e\right) \tag{4}$$

where Reynold's value is

$$r_e = \frac{\rho V d_h}{\mu} \tag{5}$$

and hydraulic diameter is

$$d_h = \frac{2mn}{m+n} \tag{6}$$

V is the mean velocity in the micro-sized channel and ρ is fluid density.

3. Results

Microchannels also vary in dimensions like length, width, height, and aspect ratio. The geometry of the microchannel affects the pressure built up in the microchannel. Both longer microchannels and smaller cross-sections result in higher pressure. Pressure in the microchannel should be managed carefully, as the excess pressure might result in the microchannel leaking or bursting. For a Polydimethylsiloxane microfluidic chip, pressure usually should be maintained below 200 kPa, or it can be 300k Pa maximum.

Using the uFluidix online calculator, the pressure-flowrate of microflow is calculated. Also, for the same calculations, the microchannel dimensions assumed are shown in Table 1. These calculations are based on the Poiseuille formula for pressure in a rectangular microchannel with laminar flow [20].

Table 1
Rectangular Microchannel dimensions assumed

Sl. No.	Shape	width	Height(depth)	Length
1	Rectangle	300 µm	200 µm	10cm

For the study, water with a density of 1000 Kg/m^3 is considered at 20 °C temperature and a viscosity of 0.001 Pa.s. Flow velocity at the inlet varies in range (1-10) mm/s with a difference of 1 mm/s. Inlet velocity variations led to the variation of pressure measurement in the range of (0.52-5.17) mbar, the calculated flow rate is in the range of (3.60-36.00) µL/min. These measurement ranges resulted in the laminar flow with a Reynolds number range (0.24-2.40) with a wall shear stress range (0.3-3.0) dyn/cm^2.

For the rectangular microchannel dimensions assumed in Table 1, the flow rate calculations for the variation in pressure are recorded in Table 2 and plotted in Figure 5. For the water flow in a rectangular microchannel, the relationship between the pressure and flow rate is linear. Pressure variations influenced the flow rate values.

Table 2
Flowrate calculated for variation in the pressure of water flow in rectangular microchannel

Sl. No.	Velocity (mm/s)	Pressure (mbar)	Flow Rate (μL/min)
1	1	0.52	3.60
2	2	1.03	7.20
3	3	1.55	10.80
4	4	2.07	14.40
5	5	2.59	18.00
6	6	3.10	21.60
7	7	3.62	25.20
8	8	4.14	28.80
9	9	4.66	32.40
10	10	5.17	36.00

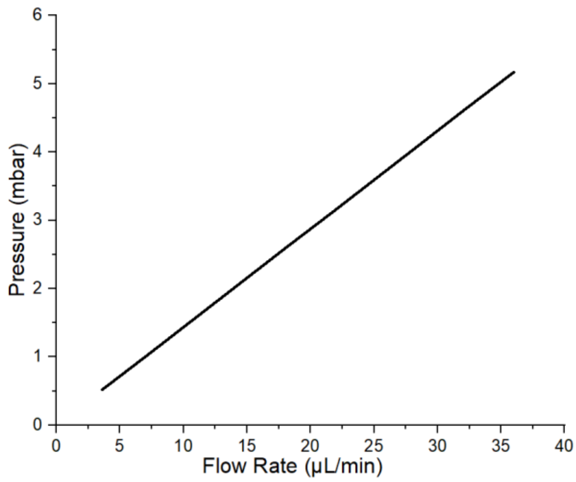

Fig. 5. Plot of the pressure and flowrate values for water flow in a rectangular microchannel

4. Conclusions

Microfluidics, an interdisciplinary field, is extending itself in multidimensions by getting flourished in biological/chemical/electro-mechanical application areas. Microchannel is also an important segment of all microfluidic devices. The microchannel's shape, wall parameters, and dimensions will vary under different applications.

For any microfluidic applications, understanding the microflow dynamics is vital for the working quality of microflow systems. Microflow dynamics are inspected by measuring microflow parameters, where microflow sensors come into the picture. Microflow sensors depend on the basic principles of microflow dynamics.

Intense research has been carried out on the cooling process of the microfluidic area. The rectangular microchannel is the most widely used in cooling applications. The Hagen–Poiseuille law bridges the microflow parameter variations and microflow sensor measurement.

For a rectangular microchannel, a variation in inlet velocity results in a variation in pressure. The variation in pressure influences the flow rate measurement of the microflow sensor.

Liquid handling in most of the applications in the microfluidic field runs around microflow rate measurement and microflow rate control. The applications of micro flowrate measurement are chemical/pharmaceutical synthesis applications, medical applications, especially drug delivery, flow manipulation applications like mixing, blending, etc. The presented micro-flowrate sensor technique can become one of the methods used in these applications.

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References

[1] Kukura, Joseph, Paulo Campos Arratia, Edit S. Szalai, Kevin J. Bittorf, and Fernando J. Muzzio. "Understanding pharmaceutical flows." *Pharmaceutical technology* 26, no. 10 (2002): 48-73.

[2] Halilovič, Miroslav, Janez Urevc, and Pino Koc. "Prediction of recirculation flow rate for icing prevention in water intake supply systems of nuclear power plants." *Cold Regions Science and Technology* 161 (2019): 63-70. https://doi.org/10.1016/j.coldregions.2019.02.013

[3] Raj, A., and A. K. Sen. "Entry and passage behavior of biological cells in a constricted compliant microchannel." *RSC advances* 8, no. 37 (2018): 20884-20893. https://doi.org/10.1039/C8RA02763C

[4] Gudekote, Manjunatha, and Rajashekhar Choudhari. "Slip effects on peristaltic transport of Casson fluid in an inclined elastic tube with porous walls." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 43, no. 1 (2018): 67-80.

[5] Li, Xuejiao, and Takashi Hibiki. "Frictional pressure drop correlation for two-phase flows in mini and micro multi-channels." *Applied Thermal Engineering* 116 (2017): 316-328. https://doi.org/10.1016/j.applthermaleng.2017.01.079

[6] Gudekote, Manjunatha, Rajashekhar Choudhari, Hanumesh Vaidya, and Kerehalli Vinayaka Prasad. "Peristaltic flow of Herschel-Bulkley fluid in an elastic tube with slip at porous walls." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 52, no. 1 (2018): 63-75.

[7] Balachandra, H., Choudhari Rajashekhar, Hanumesh Vaidya, Fateh Mebarek Oudina, Gudekote Manjunatha, and Kerehalli Vinayaka Prasad. "Homogeneous and heterogeneous reactions on the peristalsis of bingham fluid with variable fluid properties through a porous channel." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 88, no. 3 (2021): 1-19. https://doi.org/10.37934/arfmts.88.3.119

[8] Mondal, A., and G. C. Shit. "Transport of magneto-nanoparticles during electro-osmotic flow in a micro-tube in the presence of magnetic field for drug delivery application." *Journal of Magnetism and Magnetic Materials* 442 (2017): 319-328. https://doi.org/10.1016/j.jmmm.2017.06.131

[9] Duryodhan, V. S., Rajeswar Chatterjee, Shiv Govind Singh, and Amit Agrawal. "Mixing in planar spiral microchannel." *Experimental Thermal and Fluid Science* 89 (2017): 119-127. https://doi.org/10.1016/j.expthermflusci.2017.07.024

[10] Manshadi, Mohammad KD, Mehdi Mohammadi, Leila Karami Monfared, and Amir Sanati-Nezhad. "Manipulation of micro-and nanoparticles in viscoelastic fluid flows within microfluid systems." *Biotechnology and Bioengineering* 117, no. 2 (2020): 580-592. https://doi.org/10.1002/bit.27211

[11] Saengsikhiao, Piyanut, and Chayapat Prapaipornlert. "Low GWP Refrigerant R1234yf, R1234ze (z), R13I1 as an Alternative to New Zeotropic Refrigerant." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 98, no. 2 (2022): 80-89. https://doi.org/10.37934/arfmts.98.2.8089

[12] Zhang, Yanjun, Shuangfeng Wang, and Puxian Ding. "Effects of channel shape on the cooling performance of hybrid micro-channel and slot-jet module." *International journal of heat and mass transfer* 113 (2017): 295-309. https://doi.org/10.1016/j.ijheatmasstransfer.2017.05.092

[13] Gudekote, Manjunatha, Hanumesh Vaidya, Divya Baliga, Rajashekhar Choudhari, Kerehalli Vinayaka Prasad, and Viharika Viharika. "The effects of convective and porous conditions on peristaltic transport of non-Newtonian fluid through a non-uniform channel with wall properties." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 63, no. 1 (2019): 52-71.

[14] Baliga, Divya, Manjunatha Gudekote, Rajashekhar Choudhari, Hanumesh Vaidya, and Kerehalli Vinayaka Prasad. "Influence of velocity and thermal slip on the peristaltic transport of a herschel-bulkley fluid through an inclined porous tube." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 56, no. 2 (2019): 195-210.

[15] Sengupta, Joydip, Arpita Adhikari, and Chaudhery Mustansar Hussain. "Graphene-based analytical lab-on-chip devices for detection of viruses: A review." *Carbon Trends* 4 (2021): 100072. https://doi.org/10.1016/j.cartre.2021.100072

[16] Grzybowski, H., and R. Mosdorf. "Dynamics of pressure drop oscillations during flow boiling inside minichannel." *International Communications in Heat and Mass Transfer* 95 (2018): 25-32. https://doi.org/10.1016/j.icheatmasstransfer.2018.03.025

[17] Li, Di, and Xiangchun Xuan. "The motion of rigid particles in the Poiseuille flow of pseudoplastic fluids through straight rectangular microchannels." *Microfluidics and Nanofluidics* 23 (2019): 1-11. https://doi.org/10.1007/s10404-019-2224-z

[18] Shen, Feng, Mingzhu Ai, Jianfeng Ma, Zonghe Li, and Sen Xue. "An easy method for pressure measurement in microchannels using trapped air compression in a one-end-sealed capillary." *Micromachines* 11, no. 10 (2020): 914. https://doi.org/10.3390/mi11100914

[19] Fung, Chang Kai, and Mohd Fadhil Majnis. "Computational Fluid Dynamic Simulation Analysis of Effect of Microchannel Geometry on Thermal and Hydraulic Performances of Micro Channel Heat Exchanger." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 62, no. 2 (2019): 198-208.

[20] https://www.elveflow.com/.