

Influence of outlet channel width to the flow velocity and pressure of a flow focusing microfluidic device

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Abstract. Microencapsulation using flow focusing microfluidic devices attract great interest because of the simple fabrication technique using polymeric material. Simulation of the microfluidic device provides the advantage of reducing the waste of material before actual implementation of the fabrication. This paper reports the design of a flow focusing microfluidic device based on emulsification of two immiscible fluids. The system was build and simulated in COMSOL Multiphysics software by varying the outlet width in examining the effects of the flow and pressure at the outlet. The simulation results reveal that both the flow rate and the pressure decreased dramatically when the ratio of outlet channel to inlet channel (R) is greater than 2. The width of the outlet is critical in ensuring the flow of microcapsules without accumulation of microcapsules at the output pool due to the poor flow rate at the outlet channel and avoidance of leakage problem. The recommended R to achieve the objective of microencapsulation is between 2 and 4.

1. Introduction

Microfluidic device is a network of microchannels designed to perform specific functions for fluid dilution, mixing and splitting [1, 2]. The technology of microfluidic enables new tools for biomedical engineering, molecular biology, drug delivery and food industry [1, 3, 4]. One of the main applications of microfluidic is in the formation of micro or nanodroplets for containment of organic and inorganic materials for biochemical [5] and tissue engineering [5, 6]. The system gains popularity due to the advantages of providing accurate processing, low energy and reagent consumptions [1].

Flow focusing which works on the principle of emulsification is one of the mechanisms which can be performed by the microfluidic device to generate droplets. A T-junction or crossed-junction (flow focusing) are the most commonly used geometry to direct continuous flows of two channels that intersect with a downstream channel. In a water-in-oil system, the continuous flow is usually the oil



phase of the higher viscosity while the dispersed flow contains the particles, organism, chemical or dye in solutions with a lower viscosity [1]. With the streams of the continuous phase at a higher flow rate, this creates a shear pressure that “pinch off” the disperse phase at a lower flow rate leading to the formation of droplets at the output channel. The inflow of fluids are usually injected by active infusion pumps in which, the infusion rates of streams can be controlled. Tice et. al. has investigated the effect of viscosity to the size of droplets at the T-junction [7]. Other works revealed that the droplet size is affected by the flow rates of the oil phase [8] and the geometrical dimension of T-junctions [9].

It seemed that the dimension of the channels of the junction could influence the droplets formation. Hence, optimising the geometry of a flow focusing junction has to be established. The purpose of the present study is to investigate the width of the outlet channel in influencing the flow focusing junction designed for producing water-in-oil droplets. Special attention was given to demonstrate how the size of the outlet can affect the pressure and flow at the crossed junction.

2. Design and simulation of the microfluidic device

The microfluidic pattern was designed in the COMSOL Multiphysics software based on the requirements to perform emulsification at the crossed junction in which the continuous (paraffin oil) and disperse (sodium alginate) phases were intersected and combined into a downstream channel (Figure 1). An inlet (inlet 1) with two splits channels was assigned to flow the two continuous streams of paraffin oil which will be perpendicular and intercepted with the second inlet (inlet 2) of the disperse flow of sodium alginate at a crossed junctions, leading to the outlet of the microfluidic device (Figure 1). The inlet 2 channel is tapered to form the inlet channel at smaller width of 500 μm . The outlet will be connected to a pool of calcium chloride solution in which the sodium droplets polymerised into microcapsules of calcium alginate [6]. In the emulsion phase, the minute droplets of the sodium alginate will be finely dispersed in the miscible oil phase which is a water-in-oil system.

The model for simulation is as shown in Figure 1. Inlet and outlet channels were both designed with a width of 500 μm initially and a depth of 300 μm . The ratio of the outlet channel width to inlet channel width is defined as $R = I_n1/I_n2$. The inlet 2 channel has a width of 4000 μm and depth of 300 μm . The crossed junction was designed with a 500 μm of width and 300 μm of depth. Subsequently, the outlet width was varied to study the effects of different width of outlets to the fluid flow rate and pressure of the microchannels. The simulations were performed for outlet width varying from 500 to 3000 μm at an increment of 500 μm .

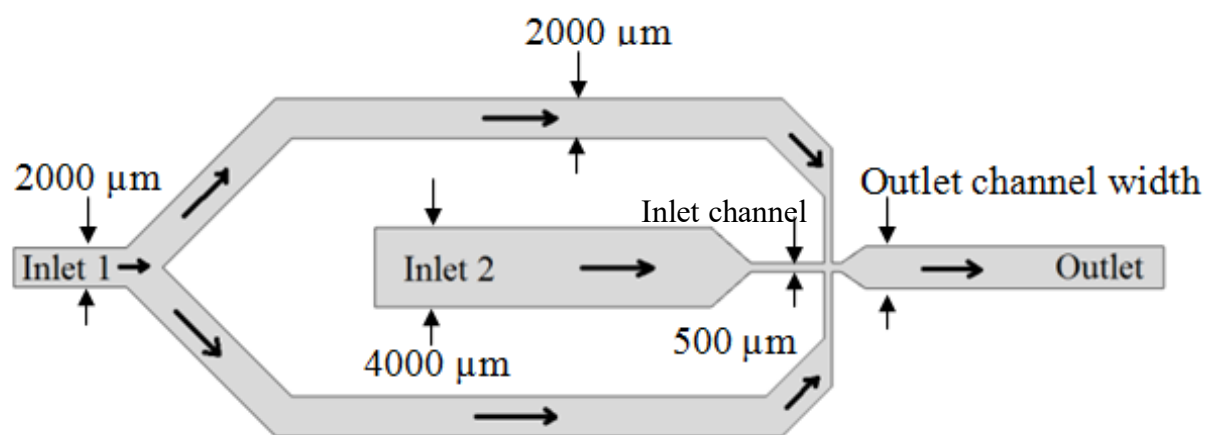


Figure 1. Initial design of a flow focusing microfluidic device.

Table 1. The specification of sodium alginate and paraffin oil [10].

	Density (kg/m ³)	Dynamic viscosity (mPa·s)
Sodium alginate	1601	20
Paraffin oil	890	46.96

Based on the computational fluid dynamic (CFD) model, the boundaries of the model were set as no slip condition which is a hydrophobic condition similar to poly-dimethylsiloxane (PDMS). The density (kg/m³) and dynamic viscosity (Pa·s) of the sodium alginate and paraffin oil were set for both inlet 1 and 2 as listed in Table 1 [10]. In the simulation, inlet 1 and inlet 2 were purged with paraffin oil and sodium alginate that were assigned as the continuous and disperse phases, respectively.

The flow rate was pre-fixed before the simulation of the model. For this model, a high flow rate at 5000 µl/min was set for the paraffin oil (continuous phase), while a lower flow rate at 300 µl/min was set for sodium alginate (disperse phase). The two flow rates suggested were the maximum flow rates of continuous and disperse phases that could optimise flow and pressure for a microfluidic device to generate microbeads without failure [11]. In considering the linear channels design, laminar flow was assumed for the simulation of the microfluidic device. The dynamic of the fluid flow can be described by the continuity equation:-

$$A_1\mu_1\rho_1 = A_2\mu_2\rho_2 \quad (1)$$

where, A is the area (m²), μ is the velocity (m/s) and ρ is the density (kg/m³).

The channel width is expected to have an influence to the velocity of fluid as indicated by equation (1). The pressure of the fluid is associated with the velocity of the fluid as indicated by the Bernoulli's equation:-

$$\frac{P_1}{\rho g} + \frac{\mu_1^2}{2g} = \frac{P_2}{\rho g} + \frac{\mu_2^2}{2g} \quad (2)$$

where, P is the pressure (kN/m³), μ is the velocity (m/s), ρ is the density of fluid (kg/m³) and g is the gravity (9.81 m/s²).

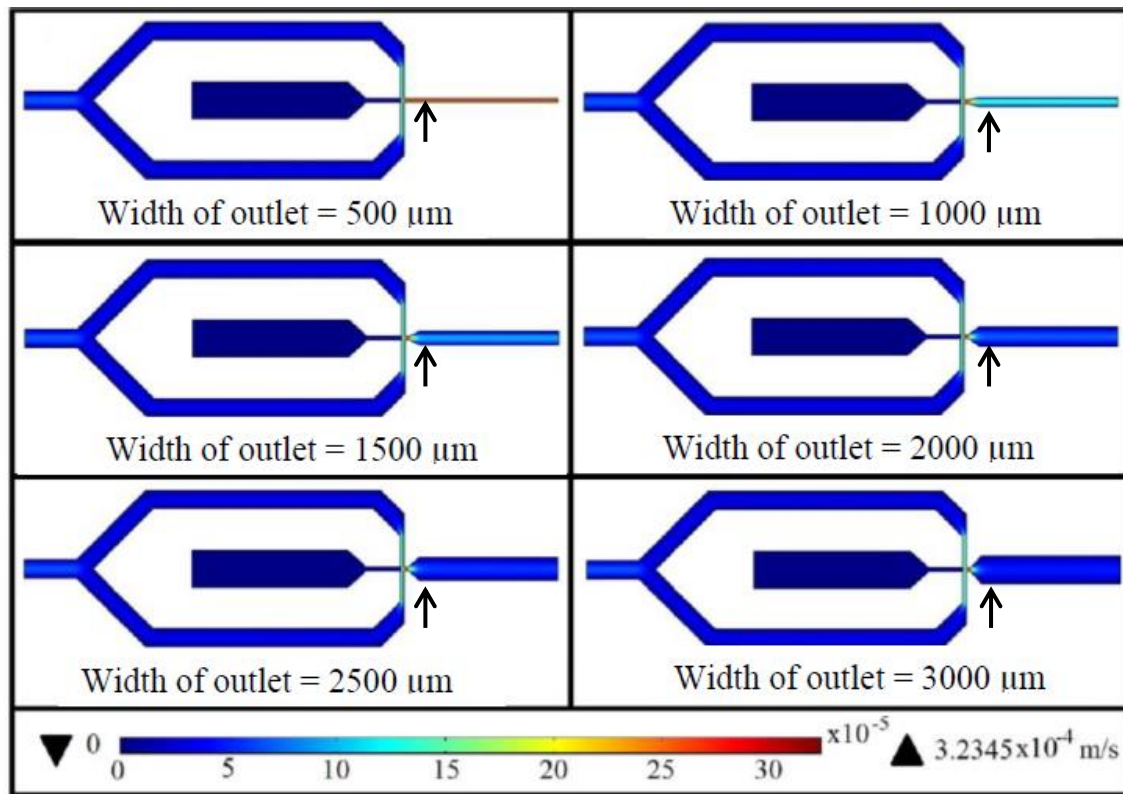
The subscripts 1 and 2 denote the parameters for estimating velocity and pressure of fluid flow in channel 1 and 2. The parameters discussed are important inputs that were included in the simulation of the microfluidic model established.

3. Results and discussion

Figure 2a shows the simulation results of the fluid focusing microfluidic channel with various channel width of the outlet. Figure 2b shows that the fluid velocity is inversely associated with the ratio of the outlet/inlet width. At an equal width of 500 µm for the inlet and outlet channels ($R = 1$), the velocity of the downstream outlet channel was indicated with higher flow velocity at approximately 3.23×10^{-4} m/s. A higher flow velocity at the narrow outlet channel than the inlet channel ($R=1$) is postulated to induce back flow problem. Nonetheless, this design may not be encouraged due to the strong flow velocity and high pressure (Figure 3) at the narrow outlet channel that might cause leakage of the channel in a microfluidic device. At $R = 2$ (Figure 2b), this situation could be improved in which the flow at the outlet channel decreased drastically to 1.2×10^{-4} m/s. A small area of higher velocity still found at the junction but larger area with lower flow velocity (1.2×10^{-5} m/s) reduced the pressure at

the junction (Figure 3). This agrees with the principal of continuity [12] that the velocity decreased when fluid flows from small to big area.

a)



b)

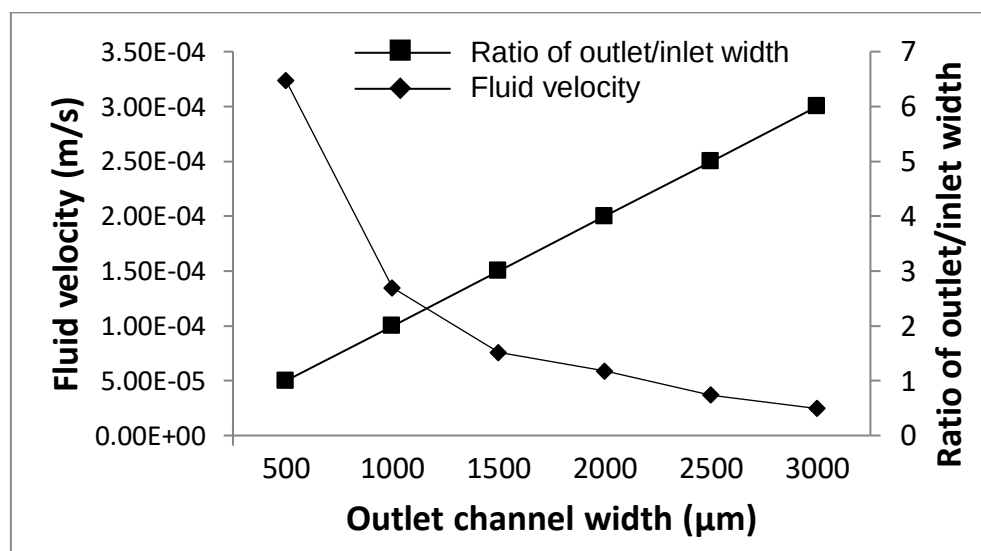
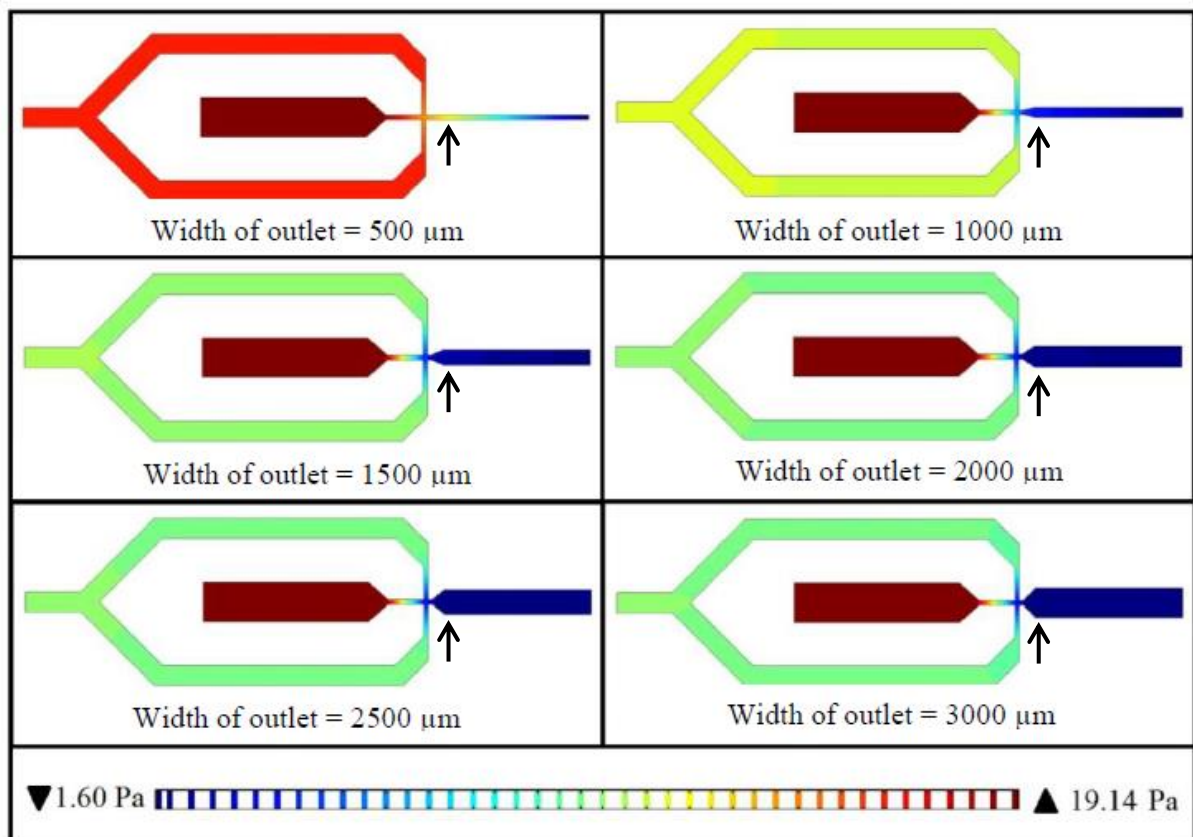


Figure 2. (a) Effects of the outlet width to the fluid flow velocity in simulations. The arrows indicate the point where the reading was taken. (b) The relationship of fluid velocity and ratio of R to the outlet channel width.

a)



b)

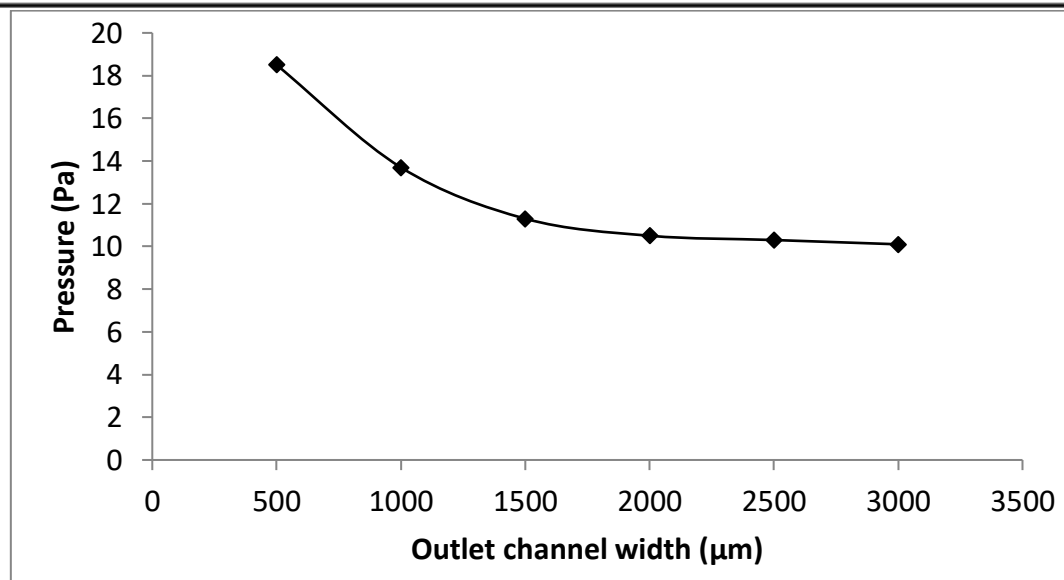


Figure 3. (a) Effects of the outlet width to the pressure in simulations. The arrows indicate the point where the reading was taken. (b) The relationship of the outlet width to the pressure.

The forward flow of both inlets can be focused forward that there should not be back flow issue at the crossed junction of the channels. As the outlet channel further increased ($R = 3$ to 6 in Figure 2b), the flow velocity of the fluid at the outlet decreased gradually as the width of the outlet increased (Figure

2b). Overall, the velocity decreased non-linearly with the change of outlet channel width at a fixed interval. The cross-over point between the ratio of outlet/inlet and the fluid velocity indicated the minimum design limit for the outlet channel width.

The pressure at the channel is important to be controlled in order to ensure that fluid pressure is not high enough to cause leakage which is a common problem in microfluidic device fabrication. Relatively, the decrease in fluid velocity has a relation to the decreased pressure of the channel (Figure 2b and 3b). The pressure decreased when the velocity of the fluid flow decreased and this is in good agreement with the Bernoulli's equation [20]. In this design, a bottle neck before the crossed junction created high pressure at inlet channel, where, the fluid flow from large to small channel is regulated by equation (1). The pressure remained high regardless of the outlet channel width. The pressure of the outlet channel stabilised at 10.3 Pa once the width is at $R = 3$. When $R = 1$, The shear pressure from the continuous phase and inlet were extremely high at approximately 19.3 Pa that may not enable the formation of droplets. The condition in which the shear forces from the lateral channels (continuous phase) higher than the inlet channel (disperse phase) must be satisfied. This can be achieved when $R > 1$. However, outlet channel with a width larger than 3000 μm that allows spaces for accumulation of droplets may result in clogging of the calcium alginate at the tube immersed in the calcium chloride solution practically. Both simulation results suggested that the width of the outlet between 1000 and 2000 μm could provide lower pressure and velocity of fluid flow which might prevent fluid leakage from the microfluidic device.

4. Conclusion

A microfluidic flow focusing device was designed and simulated to perform emulsification of the continuous and disperse phases of two liquids. The outlet channel with tapered design at the inlet and outlet channels could enable droplets formation. Narrow channels with an outlet/inlet ratio, R , less than 1 could induced high pressure that might cause leakage in the microfluidic device and back flow problem. An outlet width larger than 2000 μm or $R > 4$ may cause clogging at the output channel. Via the simulation result obtained for the design of the current work, the outlet width between 1000 and 2000 μm ($2 < R < 4$) was suggested for fabrication of a flow focusing microfluidic device due to the lower pressure and velocity presented.

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