Flow Focusing Droplet Generation Using Linear Vibration

A. Salari, C. Dalton

Department of Electrical & Computer Engineering, University of Calgary, Calgary, AB, Canada

Abstract: Flow focusing microchannels are widely used in droplet generation mechanisms. In this paper, the effect of linear vibration on the flow pattern in a flow focusing structure and the corresponding formed droplets were numerically investigated using COMSOL Multiphysics software. The results showed that vibration can be very effective on droplet formation, if the governing parameters such as vibration frequency and flow ratio are chosen accurately. This low-cost technique can be used in a wide range of applications such as drug delivery systems.

Keywords: Droplet generation, Linear vibration, Flow focusing microchannel, COMSOL Multiphysics.

1. Introduction

Droplet based microfluidics is a widely used technique in many industries such as drug delivery and lab-on-a-chip. Microbubble generation is widely used in a range of chemical, water treatment, metallurgy, and medical applications in order to facilitate heat and mass transfer, drug coating, and contrast agent generation. There are three major microchannel geometries that are used to generate micron-sized bubbles/droplets: cross flow focusing [1], co-flow focusing [2], and T-junction [3]. Fluid flow in microchannel geometries is dominated by viscous stress and pressure gradients, which both take place in low Reynolds numbers. In cross flow focusing, when two side flows reach the orifice, they make the central flow narrow and a jet-like flow is formed. If the side flows are tuned carefully, then the central flow will start to become discrete, and the central jet is converted into tiny droplets. There exists an ambient pressure chamber at the other side of the orifice. Using this mechanism, the central flow can be easily encapsulated. If gas is used as the central flow and liquid as the side flows, this mechanism will produce microbubbles [1]. In this paper, the effect of linear vibration of the microchannel body on the microdroplet generation regime was investigated using 2D COMSOL Multiphysics.

2. Governing Equations

Laminar flow module of COMSOL Multiphysics V4.4, which is a finite element based software, were used, in which a reinitialized conservative level set method was employed. The following equations describe the method [4]. The convection of the reinitialized level set function is expressed as:

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\phi \boldsymbol{u}) + \gamma \left[\left(\nabla \cdot \left(\phi(1-\phi) \frac{\nabla \phi}{|\nabla \phi|} \right) \right) - \varepsilon \nabla \cdot \nabla \phi \right] = 0 \tag{1}$$

where, ϕ, $\boldsymbol{u}$, γ, and ε are level set function, fluid velocity, initialization parameter, and controlling parameter of interface thickness, respectively. Navier-Stokes equation is the governing equation characterizing the fluid flow as follows:

$$\rho \left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} \right) - \nabla \cdot \left(\mu (\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T) \right) + \nabla p = \boldsymbol{F_{st}}$$
$$(\nabla \cdot \boldsymbol{u}) = 0 \tag{2}$$

where, ρ, and μ are density, and dynamic viscosity, respectively. Surface tension force $\boldsymbol{F_{st}}$ can be expressed as:

$$F_{st} = \nabla \cdot \boldsymbol{T} \tag{3}$$

where T is defined as:

$$\boldsymbol{T} = \sigma \left(\boldsymbol{I} - (\boldsymbol{n} \boldsymbol{n}^T) \right) \delta \tag{4}$$

where, σ, $\boldsymbol{I}$, $\boldsymbol{n}$, and δ are surface tension coefficient, identity matrix, interface normal, and Dirac delta function, respectively. $\boldsymbol{n}$, and δ are defined as follows:

$$\boldsymbol{n} = \frac{\nabla \phi}{|\nabla \phi|}$$
$$\delta = 6|\phi(1-\phi)||\nabla \phi| \tag{5}$$

3. Use of COMSOL Multiphysics

Two different flow-focusing structures ($5°$ and $60°$ between central and side channels) were modeled in 2-dimensional system with time-dependent solver. Two-phase flow regime containing fluid2 ($\rho = 1000 \ kg/m^3$, and $\eta = 0.03 \ Pa.s$) as the continuous flow, and fluid1 ($\rho = 1.1 \ kg/m^3$, and $\eta = 2 \ \mu Pa.s$) as the dispersed one with the fluid1/fluid2 surface tension of $0.001 \ N/m$ was employed to model the interactions between the two phases at the

joining orifice. Boundary conditions on internal microchannel walls were no-slip condition. Also, moving wall condition was assigned for the channel walls in order to model the oscillation movement caused by external linear vibration, the direction of which is along the central channel. To reduce the simulation time, half of the structure was modeled using symmetry condition.

The orifice dimension was 700×400 µm, and the channels width was 800 µm. In order to decrease the inlet effect on the flow regime, an 800 µm length microchannel was added to all inlets (Figure 1). Laminar flow was assumed, and both flows were considered incompressible. However, as the velocities are much less than the speed of sound, the simulation results are valid for compressible flows as well, meaning that the modeling is valid for both microdroplet and microbubble generation techniques.

Four vibration cycles with the frequencies of 50 and 60 Hz applying to the side walls were created using triangle functions.

The discretization was then performed using fine mesh sizes, which were also controlled by the physics. Figure 2 shows the mesh size generated for the domain.
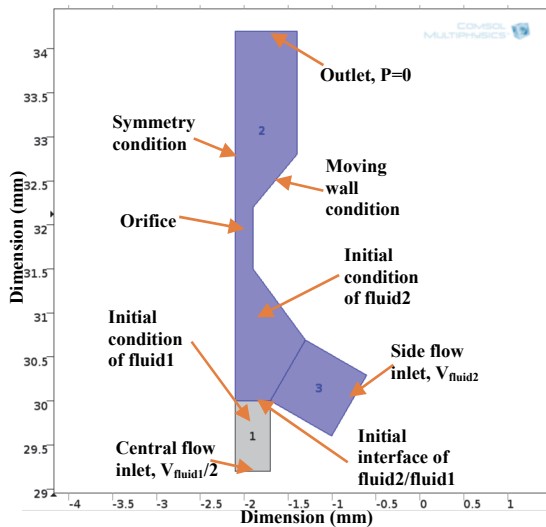
Figure. 1 The 2D structure modeled in this paper.
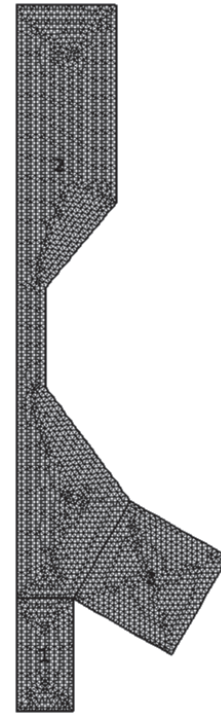
Figure 2. Mesh distribution of the structure containing more than 4600 initial elements.

4. Results

The velocity field taken at two different times during the oscillation period is shown in Figure 3, which also shows the pressure distribution of the system at these specific times. Figure 1A and 1B illustrate that the flow pattern changes during the oscillation cycle causing the pressure value oscillates as well, which can cause the central flow to be pinched into a narrow jet which can be easily encapsulated, consequently forming droplets. Figure 3 also shows that, as expected, the maximum velocities occurred in the orifice. Figure 4 shows different flow regimes obtained in one vibration cycle and for three different inlet velocity ratios (V_{fluid1}/V_{fluid2}). It shows that for V_{fluid1}= 7 mm/s, the droplet generation occurred during the second half of the vibration cycle, while in V_{fluid1}= 77 mm/s and V_{fluid1}= 47 mm/s the droplet cannot detach from the central flow jet causing a non-stable flow regime. Figure 5 shows that if the angle between the central and side flows is changed, the flow regime can be dramatically affected, resulting in a two-droplet generation mechanism. It also shows that by selecting well-

chosen inlet velocities, the mechanism can generate microdroplets with desired sizes. The simulation also showed comparable results with the experimental data taken from our previous works [1, 3].
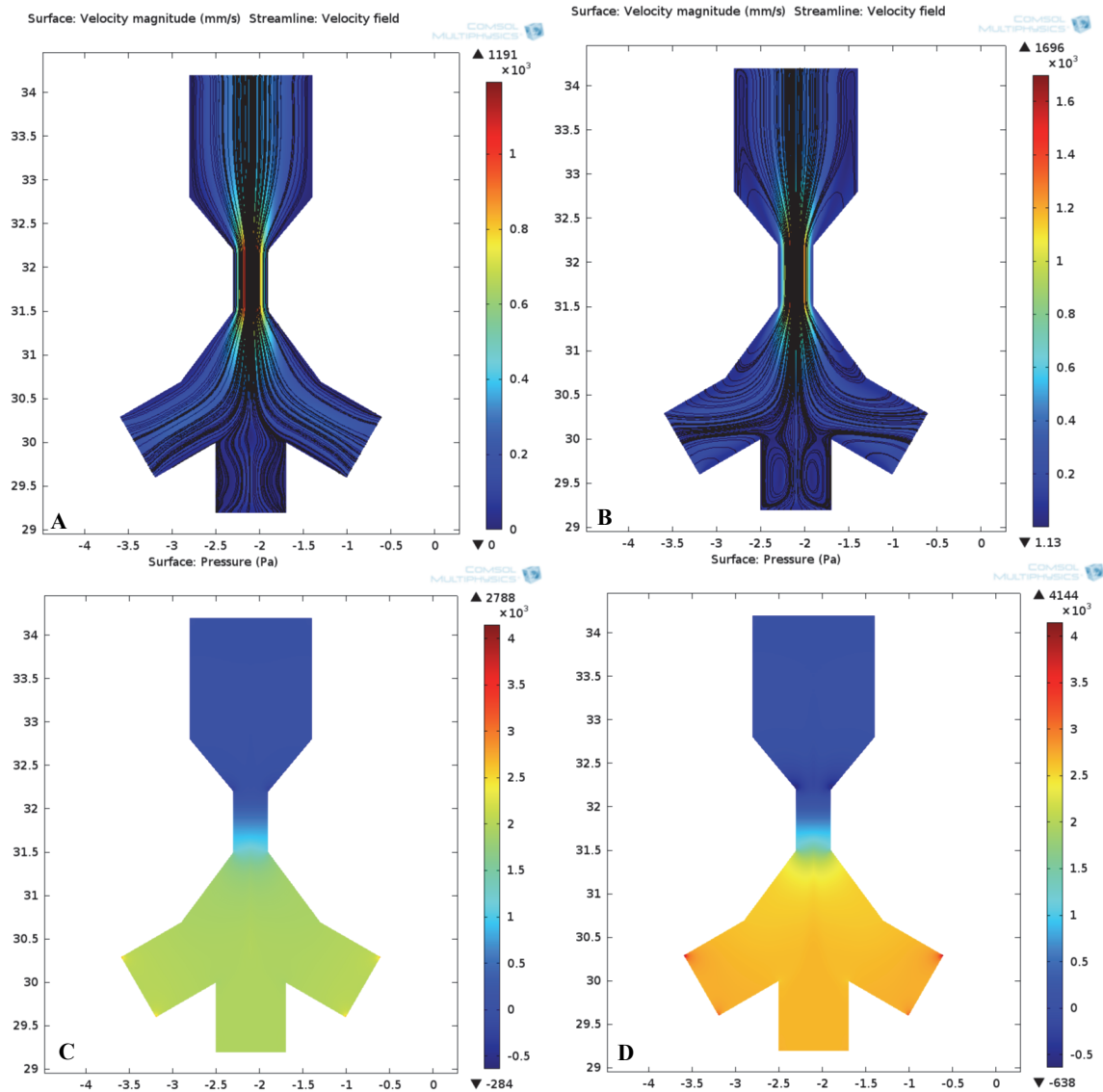
Figure 3. (A) and (B): two shots of the velocity fields for the microchannel configuration with 60˚ between central and side flow channels; vibration frequency and amplitude, central flow velocity, and side flow velocity were kept constant at 60 Hz, 1 mm, V_{fluid1}= 87 mm/s, and V_{fluid2}= 170 mm/s, respectively; (C) and (D): two shots of pressure distribution; (A) and (C): t= 0.067 s; (B) and (D): t= 0.065 s.
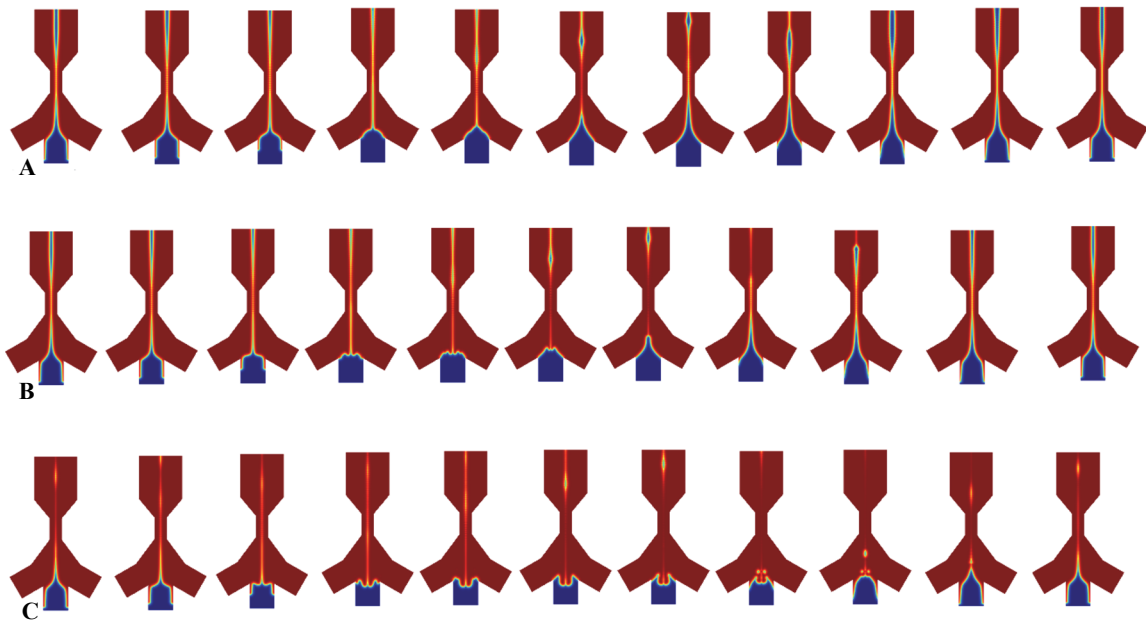
Figure 4. One vibration cycle for the microchannel configuration with $60°$ between central and side flow channels; vibration frequency and amplitude, and side flow velocity were kept constant at 50 Hz, 1 mm, and V_{fluid2}= 170 mm/s, respectively; A: V_{fluid1}= 77 mm/s; B: V_{fluid1}= 47 mm/s; C: V_{fluid1}= 7 mm/s.
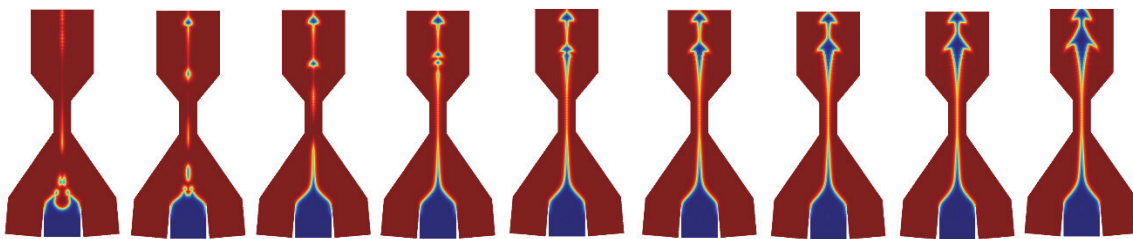
Figure 5. One single shot (at t=0.045 s) of the microchannel configuration with $5°$ between central and side flow channels; vibration frequency and amplitude, and side flow velocity were kept constant at 60 Hz, 1 mm, and V_{fluid2}= 170 mm/s, respectively; from left to right: V_{fluid1}= 7 mm/s, 17 mm/s, 27 mm/s, 37 mm/s, 47 mm/s, 57 mm/s, 67 mm/s, 77 mm/s, 87 mm/s.

5. Conclusions

In this paper, a new technique for droplet generation mechanism was numerically investigated. The results showed that applying linear vibration to the conventional flow focusing mechanism can dramatically affect the flow regime causing the structure to act more efficiently. Also, the chance of droplet generation is increased if the governing parameters, such as vibration frequency, flow ratio, and orifice dimensions are chosen accurately.

The mechanism can be used in potential applications for generation of a wide range of droplet sizes to be used in drug delivery devices, contrast agents, etc. with a low cost fabrication technique.

6. References

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7. Acknowledgements