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Micromixing and microparticle separation: A review

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Abstract – This review paper presents an overview of micromixing and the separation of microparticles using active and passive approaches. Various techniques are introduced and their main characteristics are compared. This paper reveals that hybrid and active methods can provide higher performance for microfluidic devices; however, passive approaches employ simpler structures. The type of microfluidic devices, their geometry, and the range of Reynolds number (Re) are compared for active and passive devices. Hybrid methods can be utilized to improve the mixing index of micromixers. It can be concluded that the separation of microparticles/cells is based on their size, deformability, density, inlet flow rate, strength of external forces, etc.

Keywords – Microfluidics, Micomixing, Microparticles, Separation

I. Introduction

Microfluid devices have various applications, including micromixing [1] and microparticle/cell separation [2]. Micromixing and separation processes can be performed using active and passive techniques [3]. Passive methods do not utilize external actuators; but, active devices use external forces to mix fluids or separate microparticles [4].

This paper reviews the processes of micromixing and microparticle separation using active and passive approaches. Various techniques are described and their main characteristics are compared. The type of microfluidic devices, their geometry, and the range of Re are compared for the two cases.

II. Theory

Governing equations for the micromixing process and the process of microparticle separation are as follows [1]:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla.(\rho \mathbf{u}\mathbf{u}) = -\boldsymbol{\nabla} p + \rho \mathbf{f} + \nabla.\boldsymbol{\tau} \tag{2}$$

Energy equation:

$$\frac{\partial \rho e}{\partial t} = \nabla.(\rho e \mathbf{u} - \boldsymbol{\tau}\mathbf{u} + \mathbf{q}) \tag{3}$$

In the equations, $\mathbf{u}$ is the velocity, ρ is density, $\mathbf{f}$ is force, $\boldsymbol{\tau}$ is the shear stress tensor, e is energy, p is pressure, and $\mathbf{q}$ is the heat flux vector. For the micromixing process, the convection-diffusion transfer equation is:

$$\frac{\partial C}{\partial t} + \nabla \cdot (C\mathbf{u}) = D\nabla^2 C \tag{4}$$

The mixing efficiency (ME) is calculated as follows:

$$ME = \left(1 - \left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{c_i - \bar{c}}{\bar{c}}\right)^2}\right)\right) \times 100 \tag{5}$$

where C_i is the concentration of each specie, and N denotes the number of points.

For particle separation, Newton's second law of motion is used [2]:

$$\frac{d}{dt}(m_P \boldsymbol{u}) = \boldsymbol{F}_D + \boldsymbol{F}_L \tag{6}$$

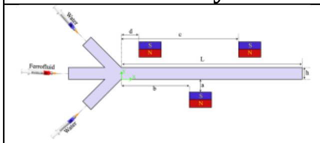
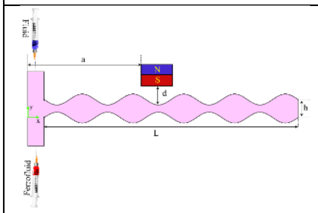
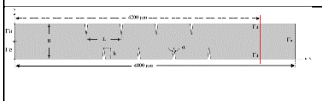
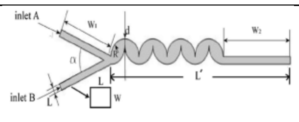
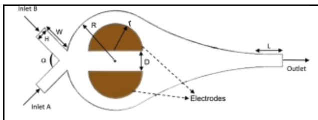
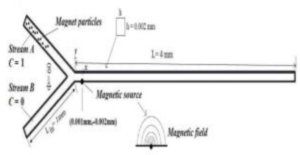
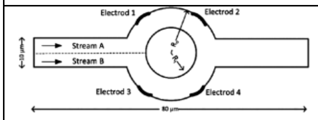
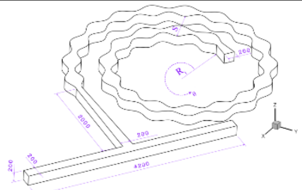
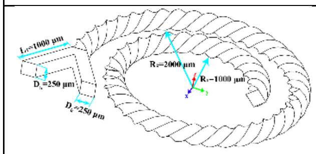
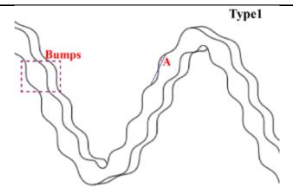
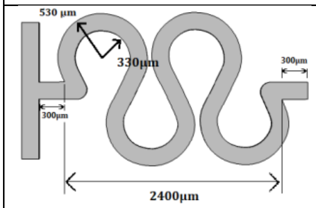
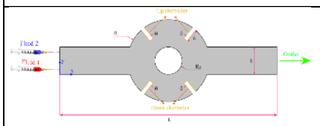
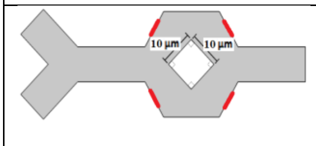
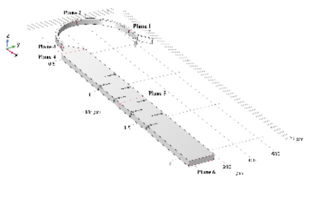
Here, m_P and $\boldsymbol{u}$ are the mass and velocity of the particles, respectively.

III. MICROMIXING

Different investigations have been carried out to mix liquids or gases in various microfluidic devices. They have employed passive and active techniques. Magnetic field [5, 6, 8, 10], acoustic field [7, 18], and electrophoresis [9, 11, 16, 17] are three types of active methods that improve mixing efficiency. It can be found that molecular diffusion is dominant when Re is low and chaotic advection plays a major role when Re is high. Obstacles, baffles, curved surfaces, etc. are employed to generate chaotic advection. Besides, active approaches enhance the mixing quality by generating vortices in the flow field.

Table 1 presents the summary of works in the field. It is demonstrated that active methods lead to higher efficiencies than passive ones. Besides, the range of the Reynolds number for active devices is relatively the same as that for passive ones. It should be pointed out that hybrid methods can be utilized to improve the mixing index of micromixers. For instance, inertial and acoustic forces are used in a high-throughput micromixer (Re = 200) [18].

Table 1. Main characteristics of passive (P) and active (A) micromixers.

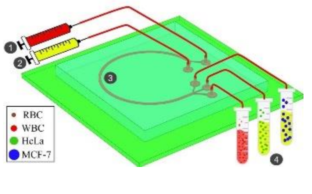
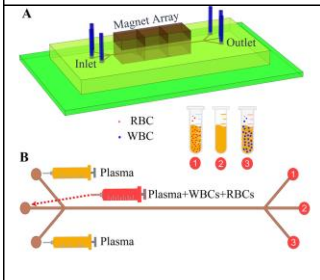
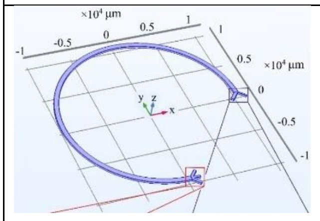
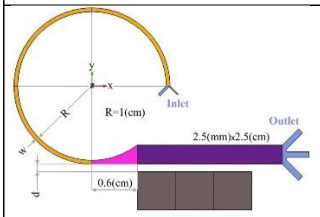
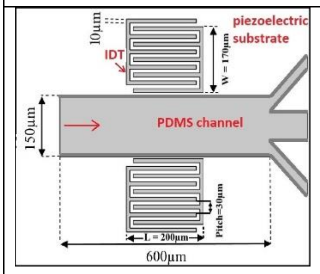
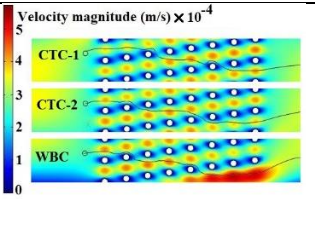
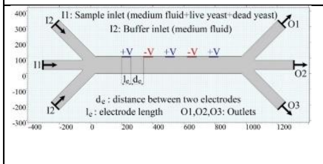
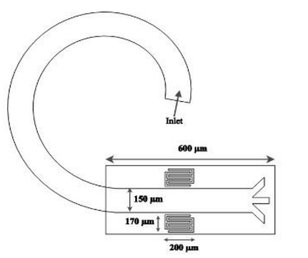
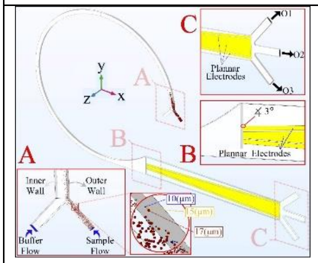
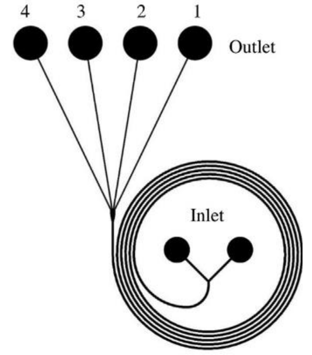
Geometry	P/A	V or Re	Ref.
	A	0.5-2 mm/s	[5]
	A	0.1-100	[6]
	A	0.5-2 mm/s	[7]
	P	9-75	[8]
	A	0.115-2.3 mm/s	[9]
	A	5-50	[10]
	A	0.01-0.2 mm/s	[11]
	P	0.1-100	[12]
	P	0.1-100	[13]
	P	0.1-100	[14]
	P	0.1-10	[15]
	A	0.05-0.2 mm/s	[16]
	A	0.05-0.5 mm/s	[17]
	A	1-200	[18]

IV. PARTICLE SEPARATION

The separation of microparticles/cells is another application of microfluidic devices [19, 20]. Like micromixers, these devices work based on passive and active techniques. They can be also employed to isolate circulating tumor cells (CTCs) from blood cells [21].

Table 2 presents the summary of works in the field. It can be concluded that the separation of microparticles/cells is based on their size, deformability, density, inlet flow rate, strength of external forces, etc.

Table 2. Main characteristics of passive (P) and active (A) separation of microparticles.

Geometry	P/A	Q or Re	Ref.
	P	30-120	[21]
	A	7.5-15 μl/h	[22]
	P	70	[23]
	A	1-15 μl/h	[24]
	A	0.2-0.6 ml/min	[25]
	P	0.1-1	[26]
	A	40-100 μm/s	[27]
	A	0.2-0.6 ml/min	[28]
	A	50-150	[29]
	P	9.17	[30]

V. CONCLUSION

An overview of micromixing and the separation of microparticles using active and passive approaches is presented in this paper. Various techniques are described and their main characteristics are compared. This paper demonstrates that active methods can provide higher performance for microfluidic devices; however, passive approaches employ simpler structures. The type of microfluidic devices, their geometry, and the range of Re are compared for two cases. It should be noted that hybrid methods can be utilized to improve the mixing index of micromixers. It can be concluded that the separation of microparticles/cells is based on their size, deformability, density, inlet flow rate, strength of external forces, etc.

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