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Numerical simulation of centrifugal serpentine micromixers and analyzing mixing quality parameters

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ABSTRACT

Centrifugal microfluidics or the Lab on a CD (LOCD) has developed vast applications in biomedical researches and analyses. Fluid mixing is an application of the LOCD. In this paper, multiple centrifugal micromixers were simulated. Various parameters were originally presumed to have an effect on mixing performance. These parameters include inlet angle, angular velocity, cross-sectional profile, perpendicular length ratio and the number of channels in series. They were each analyzed through simulations. It was gathered that the inlet angle does not significantly affect the mixing quality. Increasing angular velocity steadily increases mixing quality for all geometries. The vertical triangular cross section gives the best mixing quality and the horizontal rectangular cross section has the worst. Also both increasing the perpendicular length ratio and adding an additional microchannel in series to the original, enhances mixing.

1. Introduction

The Lab-On-A-Chip (LOC) technology has been widely used in several biomedical and chemical analyses such as the point-of-care testing (POCT) (Figeys and Pinto [1], Haeberle et al. [2], Chin et al. [3], Ryu et al. [4], Lee and Choi [5]). Comparing to other experimental platforms, the LOC has an advantage due to miniaturization, I.E. the consumption of both the sample and the reagent is drastically reduced (Srinivasan et al. [6], Fair [7]). Multiple modules could be built on the LOC for different purposes in biomedical diagnostics. However, in the LOC each module requires a separate micropump to operate. Implementing several micropumps in the LOC, complexes the design and thus multifunctional LOCs are rarely used. The LOCD is a type of LOC built on a CD-shaped disk which does not require any micropumps and could operate with a single rotational motor. The disk is mounted on a rotor shaft and its angular motion creates centrifugal force, which is used as the substitute for the micropump in order to operate different modules on the LOCD. The convenience of operation of the LOCD has made it a favorable platform for POCT and biomedical analyses such as biochemical studies (Lee et al. [8]), cell lysis and enzymatic studies (Kim et al. [9], Kim et al. [10], Lai et al. [11]) and DNA analysis (Jia et al. [12]). In order to conduct such studies and analyses, microfluidic functions such as micro valves and micromixers are developed on the LOCD (Madou et al. [13], Noroozi et al. [14], Chakraborty [15]).

For any chemical reaction to be efficient, a proper mixing of the reagents is essential. Appropriate solutions exist for mixing fluids in large scales. However, in the microfluidic scale, an effective mixing of two fluids still remains a challenge as of now. Since in microfluidic systems the flows are mostly laminar and the Reynolds number is rather small, the turbulent mixing of two fluids due to turbulence vortices would not occur. Micromixers generally fall within two categories; active micromixers which use an external force field to enhance mixing such as magnetic fields (Wang et al. [16]) or electrical fields (Wu and Liu [17]) and passive micromixers which only rely on the geometric design of the LOCD (Tofteberg et al. [18], Hessel et al. [19]).

Stroock et al. [20] developed a passive pressure-driven micromixer for mixing fluids at low Reynolds numbers. They emplaced special obstacles on the floor of the channel such that flowing over them would enhance mixing. Several micromixers have been developed for the LOCD platform. Existing micromixers mostly lack sufficient mixing performance in spite of their rather complex designs. Haeberle et al. [2] proposed a centrifugal micromixer implemented on a straight radial microchannel which worked

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based on the transverse flow caused by the Coriolis force. Although their design was the simplest centrifugal micromixer, its mixing performance was limited since it strongly depended on the angular velocity of the disk and its resulting Coriolis force. Grumann et al. [21] achieved batch-mode mixing in an LOCD with use of magnetic particles which were distributed within the two not-yet-mixed fluids. Noroozi et al., [14] presented a reciprocating micromixer composed of two reservoirs connected by U-shaped microchannels. Due to geometrical limitations, application of this micromixer in an integrated LOCD platform is problematic, despite its high mixing performance. Duffy et al. [22], Zoval and Madou [23] and Puckett et al. [24] used a serpentine microchannel system implemented on an LOCD for enzymatic analyses, bacterial analyses and protein-ligand binding analyses; respectively. They used the serpentine design only to lengthen the flow path in order to increase the diffusion time to ensure sufficient mixing without having a detailed observation of the mixing process.

The main required characteristic of an LOCD for being used in POCT diagnostics is disposability. Thus, the fabrication of the LOCD should be cost-effective and easy. Therefore, as long as an appropriate mixing performance is ensured, a simple passive design without any additional components such as electrodes or magnets is preferable to a rather complex active design. A simple passive design is convenient to manufacture on a mass-production scale for fabrication purposes and is also portable, cost-effective and easy to use. La et al. [25] designed and fabricated a centrifugal serpentine micromixer (CSM) on an LOCD and compared it to an original pressure-driven serpentine micromixer (PSM). Mixing in the PSM was limited since two laminar flows within the microchannel could only be mixed through diffusion and an inertial stirring effect happening within the sharp corners of the microchannel. However, the CSM showed superior mixing performance due to an additional secondary flow.

Finding a direct method for the quantification of mixing performance is utmostly desirable. However, this cannot be simply done, since there are quite a large number of micromixers available and yet a standard criterion to determine mixing performance does not exist (Falk and Commenge [26]). Hence, during the past couple of years, several studies have been conducted on different micromixers aiming to characterize mixer performance. Employing experimental techniques, such as fluorescent microscopy and special chemical reactions were reported in the aforementioned studies (Ehrfeld et al. [27], Falk and Commenge [26]). These methods, allow for qualitative comparisons of micromixers. However, they do not present quantitative data, such as mixing times or mixing lengths (Aubin et al. [28]).

Various methods previously employed for assessing the mixing performance of macro-scale static mixers, were used for micromixers. One method uses a Lagrangian analysis to follow the mixing of two fluid streams (Zalc et al. [29]). The mixture's homogenity could be quantified via a statistical analysis of the concentration within the mixture at any section of the micromixer. This analysis is driven from Danckwerts' intensity of segregation concept which is based on the concetration's variance ($\sigma^2{}_c$) at different locations with respect to the mean concentration (c_{avg}) (Danckwerts [30]). The mixing quality term (M.Q.) used in this paper is driven from this concept as is shown in Eq. (1). For equal volumetric feeding rates, the value of 0 for the M.Q. indicates zero mixing where a value of 1 indicates a perfect mixture.

$$\text{M.Q.} = 1 - \text{CoV} \tag{1}$$

$$\text{CoV} = \frac{\sqrt{\frac{\sum (c_i - c_{avg})^2}{n-1}}}{c_{avg}} \tag{2}$$

Where CoV is the coefficient of variation and n is the number of data points on which concentration was calculated. The CoV was analyzed at the end of each microchannel after each simulation. The mean concentration c_{avg} was calculated via a mass-flow weighted averaging over the concentration profile at the microchannel's outlet.

Alongside the M.Q., the dimensionless Reynolds and Peclet numbers could be used to characterize a micromixer's operation (Malecha et al. [31]). The Reynolds number, which characterizes the flow, is defined as follows:

$$\text{Re} = \frac{\rho u_{avg} D_h}{\mu} \tag{3}$$

Where ρ is the fluid density (kg/m^3), u_{avg} is the mean velocity (m/s), D_h is the channel's hydraulic diameter (m), and μ is the dynamic viscosity (Pa.s). The Peclet number characterizes the ratio between the mass transport due to convection and that of diffusion and is defined as Eq. (4) in which, D is the diffusivity constant (m^2/s). At high Peclet numbers, the mixing is dominated by convection.

$$\text{Pe} = \frac{u_{avg} D_h}{D} \tag{4}$$

In this paper, the mixing performance of a centrifugal micromixer is investigated through various setups. A schematic of the design is displayed in Fig. 1. A serpentine microchannel is placed on a rotating disc. The center of rotation and parametric dimensions of

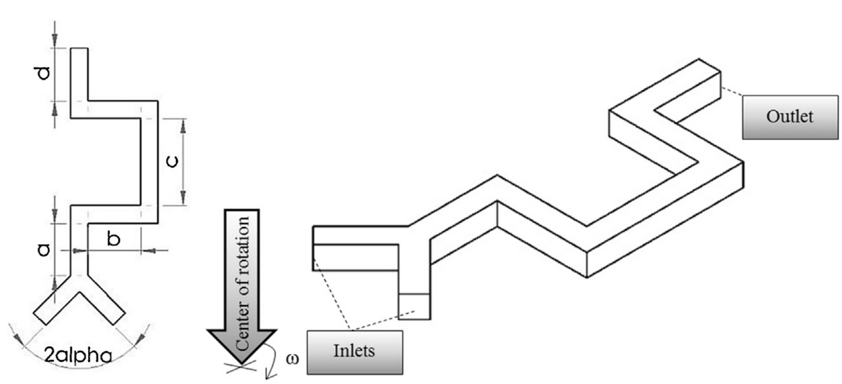

Fig. 1. Schematic of the geometry of the micromixer.