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Numerical and experimental investigation on flow and mixing in batch-mode centrifugal microfluidics

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ABSTRACT

The vortical flow leading to mixing in micro-chamber due to Euler/inertial force from continuous cyclic acceleration-and-deceleration under unidirectional rotation has been investigated both numerically and experimentally. The primary vortex as seen from numerical model during acceleration was confirmed by flow visualization by monitoring the motion of the interface between two miscible dyed liquids, and by tracking the movement of neutrally buoyant particles in the flow. In a typical test, a total of 15 cycles (equivalent to 150 s) was required to achieve uniform mixing by continuously angular acceleration-and-deceleration. This is much shorter when compared to mixing of liquids by molecular diffusion for the same test geometry (stationary) which took at least 2400 s to reach uniform mixture. For practical application, the effectiveness of mixing is quantified by a specific mixing time (*SMT*), which corresponds to the time for mixing quality, α, to reach 90% normalized by the volume of the mixture in the chamber. Lower *SMT* is indicative of more effective mixing. *SMT* was found to decrease with increasing (a) outer radius, (b) angular span, and (c) acceleration/deceleration as a result of stronger vortical flow. For small angular span (i.e. 5°) wherein mixing is slow, increasing acceleration from 17 to 34 rad/s^2 can compensate mixing, whereas for larger angular span (i.e. 20°) this is not as significant as mixing is already quite effective. Experimental measurements on *SMT* agree well with those of the numerical model.

1. Introduction

A rapid and efficient mixing at micro-scale plays a crucial role in Bio-MEMS or lab-on-a-chip (LOC) system. At this scale where the flow is strictly laminar, the system is often restricted to the viscous dominant regime with small Reynolds number (*Re*) and fluid motion is predominantly controlled by viscous forces rather than by inertial forces. This renders the flow more orderly, as such it is difficult to produce effective mass transfer in absence of chaotic flow which is normally realized by turbulence. Mixing of different species will mainly rely on molecular diffusion, which is a time consuming process and the rate of diffusive mixing can be characterized by $DA\nabla c$, where D, A and ∇c represent the diffusion coefficient, the interfacial surface area and the gradient of species concentration, respectively. Aside from the diffusion coefficient which can be enhanced by an appropriate temperature rise, diffusive mixing can be optimized by maximizing the interfacial surface area and concentration gradient. A variety of different micromixers have been developed to-date to obtain efficient mixing. Depending whether external power supply or moving parts are involved, the basic principles can be categorized into either active or passive mixing. External energy sources to "power" the mixing include ultrasound, acoustic, bubble-induced vibrations, electrokinetic instabilities, periodic variation of flow rate, electrowetting-induced merging of droplets, piezoelectric vibrating membranes, magneto-hydrodynamic action, small impellers, and integrated microvalves/pumps, etc.

Because of the simple concept, convenience in design, fabrication and implementation, as well as better integration with LOC device, passive mixers attract increasing attention and have been widely used in a number of applications. Branebjerg et al. illustrated the concept of T-shape passive mixer by developing a multi-stage and multi-layer laminating micromixer [1]. The design mainly depends on flow split and recombination. Liu et al. used serpentine geometries as the mixing channel to stretch and fold the interface between two fluids to enable efficient mixing at the microscale level [2]. Park et al. developed a rapid three-dimensional (3D) passive micromixer breaking up the flow [3]. Another method for passive mixer is to arrange obstacles or barriers with certain shapes (i.e. staggered herringbone, straight ridges) in the flow field to create a flow pattern which moves in adverse directions relative to the main flow, thus increasing the surface area and the effective diffusion of the fluids to be mixed [4–8].

Although a variety of passive mixing approaches have been reported and different efficient mixer designs have been demonstrated in the past, however the designs commonly suffer from one or more disadvantages. First, the major challenge in passive

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Nomenclature

C	concentration (g/m^3)
D	diffusion coefficient (m^2/s)
H	full height of chamber (m)
I	color intensity (–)
P	pressure (Pa)
q	velocity vector (m/s)
r	radial coordinate (m)
r_i	inner radius of chamber (m)
r_o	outer radius of chamber (m)
SMT	specific mixing time (s/L)
t	time variable (s)
Δt	half period time (s)
V	chamber volume (m^3)
z	vertical coordinate (m)

Greek symbols

Δ	small change
α	mixing quality (–)
θ	angular span of chamber, (rad)
ν	kinematic viscosity (m^2/s)
ρ	fluid density (kg/m^3)
σ	standard deviation (–)
ϕ	azimuthal coordinate (rad)
Ω	rotation speed (rad/s)

Subscripts

i	grid location, also inner
M	maximum value
o	outer

mixing is the reliance on the diffusion of the two streams at low *Re*, making efficient mixing difficult to achieve in short channel or under small residence time. Second, many designs incorporate 3D features for which fabrication can be complex as they require either multi-step lithography or aligned assembly of multiple layers. Although a number of research groups have successfully demonstrated such methods, fabrication is still time consuming and the yield remains low. Third, high pressure drop along the mixing channel may limit the capability of integrating these microfluidic components into a LOC device.

All the aforementioned passive micromixers are stationary or non-rotating. On the other hand, fast mixing can be obtained in a sample prefilled chamber or cavity in a rotating disk as illustrated in Fig. 1. Different species of the sample in the chamber mix ultimately to a homogeneous mixture as a result of the complicated flow pattern, in form of circulation and vortices, as induced by continuously changing the angular speed of the rotating disk and thus the chamber.

The flow and mixing in a rotating micro-chamber as well as continuous flow and mixing in rotating micro-channels are referred hereafter as centrifugal microfluidics. The latter offers several advantages: (a) without additional pumps and valves, it is capable of controlling and actuating release of fluids from storage reservoirs by centrifugal pumping and capillary valving to the destined chamber through channels, (b) complicated 3D structure is not required, thus the device can be easily fabricated and incorporated into a LOC system, (c) the disk can be fabricated, with disposal after-use in mind, in an economical way by mass-production from inexpensive materials such as polycarbonate.

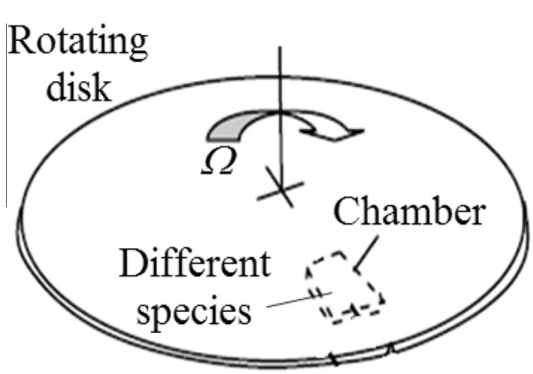

Fig. 1. Concept of rotating disk for microfluidic application.

The technology has been demonstrated in a variety of microfluidic applications [9,10].

Centrifugal microfluidics can also be used to improve mixing at micro-scale. Several studies have been carried out on continuous-flow and mixing in micro-channels [11,12]. On the other hand, Grumann et al. demonstrated batch-mode mixing in a circular 25-μl rotating chamber [13]. They reported that fast mixing can be achieved when combining rotating the chamber successively with continuously angular acceleration-and-deceleration transient scheme in the alternate rotation direction together with movement of the imbedded magnetic beads controlled by an external magnetic field.

However, the uniformity of mixing by continuously angular acceleration-and-deceleration in the same rotation direction has not been reported. In addition, the underlying vortical flow, which is of key importance leading to batch-mode mixing of fluid sample in centrifugal microfluidics, has also not been investigated. Ren and Leung [14] developed a validated model to investigate the fluid mechanics and mass transfer involved in the mixing as driven by vortical flow in the rotating chamber which is under continuously angular acceleration-and-deceleration. Two types of vortices were found: a primary vortex generated from the Euler inertial acceleration/deceleration, and a pair of toroidal vortices generated from the Coriolis acceleration acting on the primary vortex. They also found that efficient mixing can be generated from the vortical flow, and a larger chamber can accommodate larger vortices thereby facilitating mixing. Increase of maximum rotation speed and acceleration/deceleration can also intensify vortices achieving more effective mixing.

Despite of this preliminary study, there have been no experimental results as yet to verify the vortical flow pattern, especially the primary vortex. In addition, results from the numerical model require to be supported by experimental results to confirm the dependence of the effectiveness of mixing on the chamber geometry (outer radius, angular span, and height) and operating parameters (maximum rotation speed and acceleration/deceleration). In addressing these problems, investigation is conducted in the following sub-areas:

(1) With our established numerical model [14] demonstrate experimentally under continuous acceleration/deceleration the vortical flow pattern and associated primary vortex which mainly contributes to mixing in the radial–circumferential planes of the chamber.
(2) Verify the primary vortex experimentally by two flow tracking approaches, including monitoring the motion of interface between two miscible dyed liquids, and tracking the