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Experimental Investigation on Flow and Mixing in Rotating Microfluidics

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Abstract

Mixing in rotational micro-chamber has been carried out both experimentally and numerically with intent of improving mixing in viscous dominated microfluidics. In experiment, an enclosed chamber made of machined PMMA cut-out with a PDMS cover was set-up on the rotational platform. Different geometries of the chamber (on the order of several mm) with constant height yet different angular span 5, 10, 15, 20 deg. and radial extents 1.5 and 3 mm were used in the tests. While the two different dyes each occupying half of the chamber took a long time (e.g. nearly 40 minutes for a 20-degree span chamber with inner and outer radii, respectively, 35 and 36.5 mm and height 0.5 mm) for mixing by molecular diffusion in the chamber, faster mixing (about 2.5 minute) can be achieved under continuous acceleration and deceleration rotation with a linear rate of 25 rad/s^2. The time for mixing per unit volume (Specific Mixing Time - SMT) was determined experimentally as a function of geometry. The SMT increases with increasing vorticity strength as a result of increasing size of the rotating chamber and/or increasing the magnitude of the linear acceleration and deceleration rates. Mixing is also studied by numerical simulation of the tested geometry. Comparing with the experiments, we found good agreement for the SMT between test results and numerical model for small-angled chamber while the numerical model seems to under-estimate the SMT for large-angled chamber. Further, we have also verified qualitatively in the experiment the flow pattern of the primary vortex in the radial-azimuthal plane responsible, to a large extent, for mixing in the chamber. Two approaches have been taken to observe and confirm the primary vortex being set up by continuous acceleration-and-deceleration of the chamber. The first approach adopted color tracing with two miscible dyed liquids, and the second approach used neutrally buoyant particles to trace fluid particle flow in the rotating chamber.

Background

Passive mixing in microfluidics has been studied extensively [1-11] as it does not involve direct mixing of external mixing elements with the small liquid sample in microfluidics. One effective passive mixing in microfluidics is by rotating the chamber [12-26] in form of a CD, see Fig. 1. In a separate study using a numerical model presented separately [27], the authors found that complicated secondary flow, in form of vortices, in a rotating chamber was generated for mixing different species by continuous changing the rate of rotation over time until uniform mixing of the different species in the chamber has been attained. With reference to the rotating chamber, the secondary flow consists of a main vortex in the R-θ planes, generated from the d'Alembert force due to acceleration/deceleration, and is responsible for momentum and mass transfer in those planes; while two pairs of toroidal vortices, generated from the Coriolis force, is responsible for momentum and mass transfer in the direction parallel to the rotational axis. These secondary flow and vortices help to reduce the mixing length between species of a given concentration to facilitate ultimate homogenization by molecular diffusion.

In this study, we want to verify using experiments that the secondary flows exist during acceleration or deceleration of a rotating chamber. Further, we want to determine the time for mixing using reasonably achievable acceleration time schemes in rotating microfluidic. The measurements will be compared to the numerical models which simulate the test geometry and conditions.

Fig. 1 shows a schematic drawing of a rotating chamber in a CD.

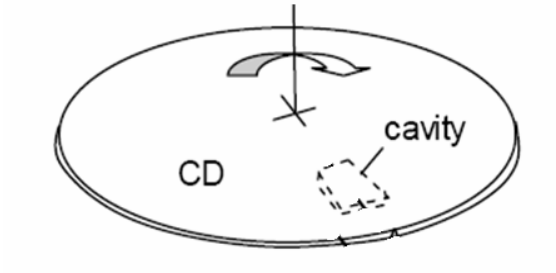

Fig. 1 – Chamber in a rotating CD.

Experiment Set-up

A test rig has been developed with a rotating platform that is capable of rotating up to a nominal maximum speed up of 1800 RPM. A CCD camera mounted onto a microscope, which is positioned at various radial locations along a bridge, is used to take images of the flow in the chamber during rotation of the CD. A dummy mass situated diametrically opposite to the camera-microscope pair is used to balance the centrifugal force generated from the camera-microscope so that there is no outstanding unbalanced force during rotation of the platform as it would cause vibration. The fluid motion can truly be observed in the rotating reference frame as simulated in Ref 27. Temperature can be maintained relatively constant using the water bath maintained at a relative constant temperature.

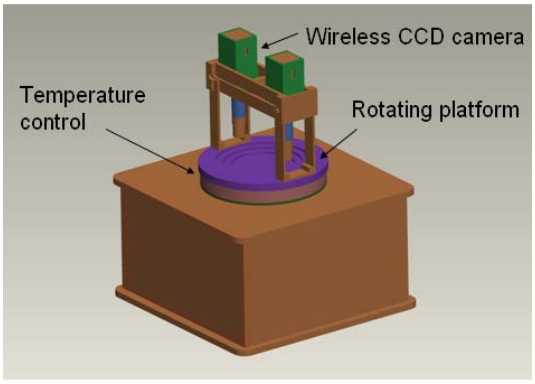

Fig. 2 – Rotating platform accommodating test chamber housed in a CD (see Fig. 1).

In the experiment, an enclosed chamber made of machined PMMA cut-out with a PDMS cover was set-up on the rotational platform. Fig. 3 shows 16 different chambers of different geometries (R_o, R_i and θ's) being tested.

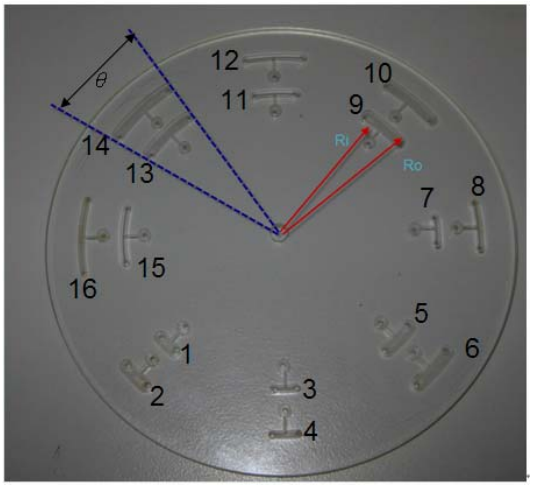

Fig. 3 – Different chamber geometries in a CD.

Flow Observation

First two different miscible liquids were used to occupy, respectively, the left (purple KMNO4) and right hand side (blue copper chloride) of the chamber, see Fig. 4. At t=0, the CD with the chambers was accelerated linearly over time in 5 seconds to 1200 RPM. Fig. 5 shows a zoom-in view of the two liquid fronts at t=4 s (when the instantaneous rotation of the chamber was at 960 RPM.) As can be seen, the liquid (dyed purple) at the large radius moves opposite to the rotation direction while the liquid (dyed blue) moved at a smaller radius in the same direction as rotation. This is indeed similar to what has been observed in Fig. 4 and Fig. 6 of Ref [27]. Neutrally buoyant particles have also been injected into the flow field for observation during acceleration and deceleration to confirm qualitatively the flow field, which is in general agreement to our numerical model [27].

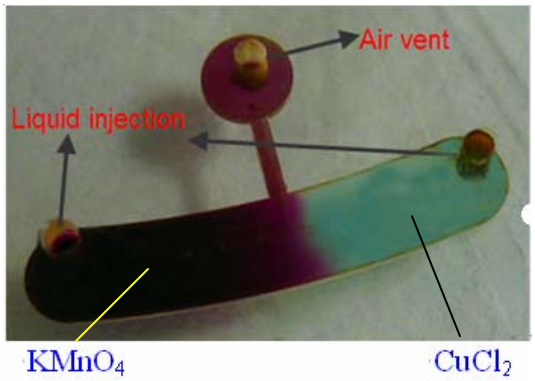

Fig. 4 – Two different color dye located in a rotating chamber before mixing.

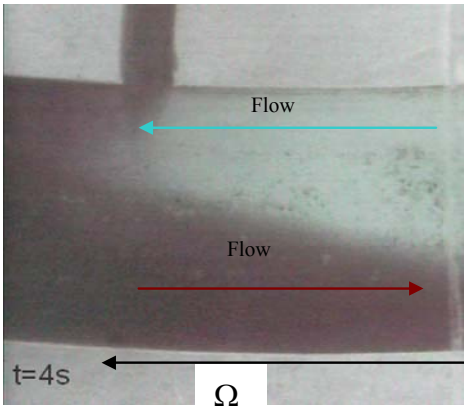

Fig. 5 – Purple liquid moves toward right at the large radius while the blue liquid moves toward left.

Test Results

Measurements have been made using a pie-shaped chamber with R_o=36.5mm and 38 mm respectively, and R_i=35 mm as shown in Fig. 6. The height H is 0.5 mm.

Videos are recorded in details the mixing progress in the chamber. Subsequently, the images acquired from the video are stored as 8-bit grey-scale bitmaps [12] and transformed into a brightness intensity histogram representing the corresponding pixel distribution in the mixing chamber in terms of the standard deviation σ, which is defined as $\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(I_i - \bar{I})^2}$, where I_i denotes the intensity at the i^{th} pixel in the image, n denotes total number of pixel, $\bar{I}$ denotes the averaged intensity. This can constitute an appropriate measure of the mixing performance. Uniform and homogenous mixing was reached such that the standard deviation level was smaller than a prescribed small tolerance level and also that the standard deviation did not vary over time.

While the two different dyes each occupying half of the chamber took a long time (nearly 40 minutes for a 20-degree span chamber with inner and outer radii, respectively, 35 and 36.5 mm and height 0.5 mm) for mixing by molecular diffusion in the chamber, faster mixing (about 2.5 minute) can be achieved much more rapidly under continuous acceleration and deceleration rotation with a linear rate of 25 rad/s^2 (accelerating to 1200 RPM in 5 seconds).

The time for mixing is normalized by the volume of liquid being mixed in the chamber to derive the specific mixing time SMT [s/μL], SMT=t/*V*, where t denotes the mixing time to reach homogeneous state and *V* denotes the chamber volume. The smaller is SMT, the more effective is the mixing, and shorter is the mixing time for a given unit volume of liquids to be mixed. Fig. 6 shows one test result wherein the CD is accelerated linearly over time to 800 RPM in 5 seconds and subsequently decelerated back linearly over time in another 5 seconds to zero speed. The acceleration/deceleration rates are 17 rad/s^2. It is clear that as the angle is increased from 5° to 20° for R_o=38 mm, SMT drops rapidly between 5° and 15° but the drop is only moderate between 15° and 20° .The drop in SMT reflects that better mixing is attained for chambers with wider angular span. This was also observed [27]. Likewise, when R_o decreases to 36.5 mm, this behavior is also observed but more pronounced with large drop again between 5° and 15° .

The numerical model [27] was used to simulate the geometry, and results of the numerical simulation (solid curves) were compared to the measurements in Fig. 6. Between 5° and 15° , the comparison between simulation and experiments are reasonable, however for larger angles 15° -20° , the simulation under-predicts the actual mixing time.

Figs. 7 and 8 compare the experimental results with numerical simulation when the acceleration/deceleration rates are 25 and 34 rad/s^2 corresponding to the maximum speed of

1200 and 1600 RPM, respectively. Similar conclusion can be drawn that smaller angles (5° and 15°) have better quantitative agreement with the numerical model despite the trend generally agrees to a large part with the numerical model.

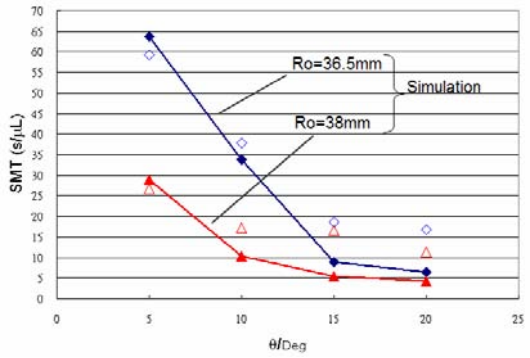

Fig. 6 – R_i=35 mm and H=0.5 mm for all 8 chambers for the two R_o=36.5 and 38 mm. The solid line segments represent prediction from numerical model. Open diamond symbols and open triangles represent measurements. Linear acceleration/deceleration rates correspond to ±17 rad/s^2.

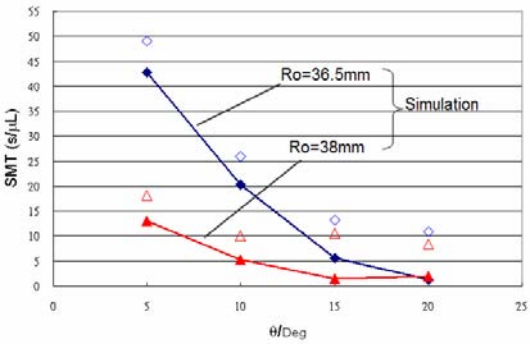

Fig. 7 – Comparison between experiments and simulation at 1200 RPM. Linear acceleration/deceleration rates correspond to ±25 rad/s^2.

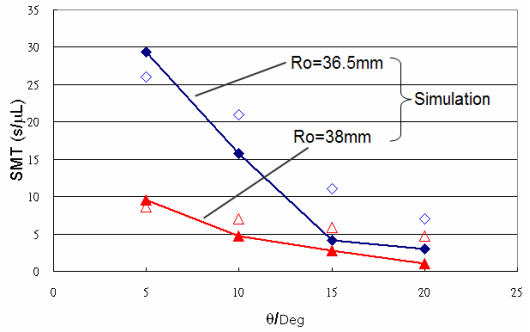

Fig. 8 – Comparison between experiments and simulation at 1600 RPM. Linear acceleration/deceleration rates correspond to ±34 rad/s^2.

Conclusions

An experimental rig has been set up for testing batch mixing in microfluidics. Two methods have been developed for flow observation. We used respectively dye and neutrally buoyant particles to confirm qualitatively the main circulation setup during acceleration and likewise deceleration. Also, we are able to use image processing technique to determine quantitatively the mixing condition of two liquids. We found that large outer radius and larger angular extent certainly can improve the mixing time per unit volume of mixture. Experimental measurements support the numerical simulation result at least for angle extending to 15 degree beyond which the simulation under-estimating the required mixing time.

Increasing rotation speed, which increases the vorticity strength, will also improve mixing as evident in comparing Figs. 6-8 with progressive shorter SMT while all other parameters are held constant.

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