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Vortex Structure and Mixing in Meandering Microchannels

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Microscale fluid flow is currently of great interest in a number of areas including micro chemical engineering and processing, as well as MEMS, biomedical and Lab on a Chip applications. Due to the small dimensions of a micro channel the flow is predominantly laminar and it is well-known that this has an important effect on the performance of transport processes, such as heat and mass transfer. For example, a mixing process can be very slow unless the channel is extremely narrow (< 10 microns), since it is limited by molecular diffusion. As a result, a very long micro channel is needed to obtain a sufficient degree of mixing. Similar arguments can be put forth for reacting flows and heat transfer applications. Although a large number of mechanisms exist for fluid contacting and enhancing mixing (multi-lamination, splitting and recombination, hydrodynamic focussing, T- and Y-junctions^[1], chaotic advection^[2-4]), these may not be particularly advantageous for increasing residence time for chemical reaction and heat transfer and therefore a long channel may still be required. Of course one of the design requirements of these miniaturised devices is that they are compact and an obvious solution is to employ meandering channel geometries. A number of works have studied the effects of meandering channels in different applications such as heat transfer^[5] and mixing in single^[6] and two phase flows^[7-10]. In general, the channel bends have positive effects, enhancing heat and mass transfer. However, some studies suggest some disadvantages of sharp angled bends, such as recirculation, widened residence time distributions and 'bubble clogging'^[8,9].

In this paper, we look at the effect of the topographical shape of the microchannel on the hydrodynamics using CFD simulations. In particular, the effect of curved bends compared with sharp angled bends on the vortex structure and mixing is studied.

The microreactor geometries consist of a meandering channel with rectangular cross-section (height, $h = 500 \mu\text{m}$, width, $w = 1000 \mu\text{m}$ and length, $l \approx 30 \text{ cm}$) and two inlets, which are normal to one another. The bends in the channels are either semi-circular or right-angled, as shown in Figure 1. The numerical simulation of the flow and mixing in the microchannels is performed using ANSYS-CFX10, which is a general purpose commercial CFD package. Simulations are carried out in the laminar flow regime with several Reynolds numbers (Re) < 100 . Ethanol at $25 \text{ }^\circ\text{C}$ and 1 atm is used as the operating fluid. In order to evaluate mixing performance, mass-less fluid particles are released from one of the channel inlets and are followed using a Lagrangian particle tracking method. This approach avoids the introduction of numerical diffusion, which results if a scalar is tracked, and confuses the mixing behaviour. The results are then quantified by using spatial statistical methods to evaluate the evenness of the spatial distribution of the tracer and the variance of the tracer distribution with respect to a homogeneous mixture^[11]. The effect of channel geometry on residence time is also investigated by determining the residence time distribution.



Figure 1: Microchannel geometries used in this study with $w = 1000 \mu\text{m}$, $h = 500 \mu\text{m}$ and $l \approx 30 \text{ cm}$. (a) Curved meandering channel, (b) angled meandering channel.

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