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Flow investigation in a microchannel with a flow disturbing rib

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HIGHLIGHTS

- We studied the flow around a flow-disturbing rib in a microchannel.
- The flow was characterized using both the μ-PIV and the electrodiffusion techniques.
- A validated CFD code was used to assess the effect of key design parameters.
- The blockage ratio and the Re greatly affect the formation of recirculation zones.
- We proposed correlations for predicting the length of the bottom recirculation zone.

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ABSTRACT

The purpose of this work is to study the flow around a flow-disturbing rib in a rectangular microchannel and to investigate the effect of key design parameters (i.e. the rib height and length as well as the *Reynolds* number) on the size of the *reattachment length* of the recirculation zones and the *wall shear stress* profiles in the vicinity of the rib. Initially the wall shear rate along the channel as well as the velocity field were experimentally determined using the *electrodiffusion technique* and the *μ-PIV* method, respectively. The experimental results are then used for validating a *CFD* code. Finally, the *CFD* code was employed for investigating the effect of the design parameters on the flow characteristics by performing a parametric study based on the *Design of Experiments* (*DOE*) and the *Response Surface Methodology* (*RSM*). It was found that the recirculation length in the laminar regime is affected mainly by the *Re* value and the rib height, whereas in the turbulent regime it is affected strongly by the rib height and slightly also by the rib length. Based on our results two new correlations, which can predict the length of the bottom recirculation zone with reasonable accuracy, are proposed and can be used for the design of microdevices.

1. Introduction

The intensive development of microfluidic technologies resulted in a considerable range of microfluidic systems for a variety of applications. The results of this research and technology explosion in the last decade has led to the identification of microfluidics as one of the most promising fields in modern process engineering. The main advantages of micro-systems are their high surface-to-volume ratio, the increased efficiency and operability of the microdevices and the opportunity to control the transfer rates and state conditions in a way that is optimal for the desired results (Kockmann, 2006).

In the microscale, mixing, a fundamental unit operation for many other processes, can be induced both by active and passive methods. In passive micromixers, there is no need for external energy, while the mixing performance is enhanced by modifying the flow path, creating and increasing contact time between fluids. In the macroscale, the flow over a *Backward Facing Step* (*BFS*) is considered a benchmark and has been thoroughly studied either experimentally (Armaly et al., 1983; Lee and Mateescu, 1998; Wengle et al., 2001) or numerically (Le et al., 1997; Kaiktsis and Monkewitz, 2003). The study of liquid flow in a *BFS* geometry in a microchannel has recently attracted interest. Kherbeet et al. (2014) studied a *BFS* geometry in a microchannel and reported that the basic features observed in the macroscale (like velocity profiles and recirculation areas) remain practically the same in the micro-scale. Tien et al. (2014) performed experiments in a micro *BFS* geometry in order to validate a *3D-μPTV* technique and resolved the flow field in steady and unsteady flow conditions.

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A significant portion of the *Micro-Electro-Mechanical-Systems* (*MEMS*) involves micro-flows while *MEMS* typically find applications in biological devices like the separation of red blood cells from the plasma in a *BFS* geometry (Huang et al., 2010). In medical applications and particularly in hemodynamics the *Wall Shear Stress* (*WSS*) profiles have been identified as a major parameter that influences the formation of the atherosclerotic plaque in arteries. The progression of *atherosclerosis* leads to arterial stenosis that effectively act as forward or backward facing steps (Kanaris et al., 2012). Moreover, Caro et al. (1971) reported that flow recirculation zones formed due to arterial stenosis make the surface downstream of the stenosis prone to cholesterol deposition and eventually prompt progression of atherosclerosis disease.

In heat transfer applications a typical modification of the channel wall is an orthogonal barrier, effectively creating a step in the fluid flow path that significantly enhances heat transfer by modifying the flow field (Stogiannis et al., 2013). Although heat transfer enhancement in simplified standard geometries like backward (Vogel and Eaton, 1985; Kondoh et al., 1993) or forward (Abu-Mulaweh, 2003) facing steps has been extensively studied, to the authors' best knowledge limited research have been done for the effect of flow-disturbing rib for heat transfer applications in the microscale.

The experimental characterization of fluid flow in microscale presupposes the use of a reliable measuring technique, but the well-established methods in macroscale are not easily applicable in microchannels. Due to the small dimensions of the conduits it is challenging to employ methods that use flush-mounted sensors like the *electrodiffusion technique* (Hanratty and Campbell, 1996) typically used for near-wall flow diagnostics in larger scales. In the microscale, Huchet et al. (2007) studied the mixing performance in crossing microchannels using electrodiffusion sensors and *CFD* modeling. A common non-intrusive technique is *micro-Particle Image Velocimetry* (*μ-PIV*) which been extensively used in microfluidics for two-dimensional velocity-field measurements (Koutsiaris et al., 1999) and the investigation of liquid film characteristics (Anastasiou et al., 2013). Ait Mouheb et al. (2011) studied the flow in various micromixer designs using experimental techniques like the *μ-PIV* and the electrodiffusion ones while numerical modeling using a *CFD* code was also employed.

It is common practice in fluid flow studies to replace expensive and time-consuming experiments with validated *Computational Fluid Dynamics* (*CFD*) simulations. A *CFD* code can be used to assess the effect of important geometrical characteristics of the microchannels on various design parameters like the extent of recirculation zones in passive micromixers (Mouza et al., 2005).

The *scope* of this work is to characterize the flow around a flow-disturbing rib aiming to investigate the effect of key design specifications (i.e. geometrical characteristics and flow parameters) on the size of the *reattachment length* of the recirculation zones and the *WSS* profiles on the rib surface as well as on the upstream and downstream of the surrounding walls. These parameters have been identified as the most important in applications of microchannels like fluid mixing, heat transfer enhancement and biomedical engineering applications. It is already known that, in macroscale the reattachment lengths depend primarily on the geometrical characteristics of the channel and the fluid *Re* (Tihon et al., 2001). To perform this study a *CFD* code has been validated using experimental data from two independent methods, namely the *μ-PIV* technique for investigating the velocity field and the electrodiffusion technique for local measurement of the *WSS*. Finally, using the validated *CFD* code a parametric study is performed based on *Design of Experiments* (*DOE*) and *Response Surface Methodology* (*RSM*) techniques for predicting the length of the bottom recirculation zone as a function of the geometrical characteristics of the rib and the *Re*.

2. Experimental setup

We conducted experiments in a rectangular *PMMA* channel (0.925 mm in height (*H*), 10 mm in width (*W*) and 100 mm in length) with a rib (0.400 mm in height, *d*) located at a distance of 60 mm downstream of the inlet (Fig. 1). The channel geometry is completed by placing the top plate equipped with the electrodiffusion microsensors. The use of an *O*-ring which acts as the side walls of the conduit, prevents leakage. The nominal dimensions of the channel correspond to a blockage ratio (*BR*) of 0.43 calculated as the ratio of the rib height over the channel height. Additionally, the ratio of the channel width over the rib height gives a spanwise aspect ratio (*AR*) equal to 25, which is a critical parameter for the distinction between 2D and 3D flow. Kaiktsis and Monkewitz (2003) showed that for 2D geometries the flow can be globally stable and time-independent up to a critical $Re=1000$ value. Barkley et al. (2002) commented that the flow can be destabilized well before the critical value due to the effect of the side walls. Tihon et al. (2010) suggested that separating/reattaching flow is always affected by the value of *AR*, but for *AR* greater than 25 it can be characterized as predominantly 2D.

The *electrodiffusion technique*, which is based on the measurement of the limiting diffusion current of the ferricyanide ions reduction at a small working electrode, is used to measure local values of wall shear rate (Hanratty and Campbell, 1996). The working solution is water containing 0.025 M $K_3[Fe(CN)_6]$, 0.025 M $K_4[Fe(CN)_6]$ and 0.057 M K_2SO_4 as a supporting electrolyte. A polarization voltage (−0.6 V) is applied on the working electrode and current is measured under diffusional limiting conditions. For a single strip segment the current-signal, *I*, can be related to the instantaneous value of *Wall Shear Rate*, s_w, through the formula:

$$I=0.807zFc_0wl^{2/3}D^{2/3}s_w^{2/3} \tag{1}$$

where *z* is the number of electrons involved in the electrochemical reaction, *F* is the Faraday constant, *l* is the length of the strip in the main flow direction, *w* is its width, while c_0 is the bulk concentration of the ions and *D* their diffusivity in the solution. The measured current from each stripe is converted to voltage signals, amplified and recorded by a *PC*. Measurements are performed with a sampling frequency of 2 kHz.

The micro sensors consist of twenty cathodes of 160 μm length each, placed at a distance of 40 μm from each other and flush-mounted on the top wall of the microchannel (above the rib). A larger anode is positioned away from the rib inside the channel. The *μ*-structures were built on the channel wall using a *UV-lithography* technique while they are later filled with gold using galvanic deposition as described in detail elsewhere (Schrott et al., 2009). The wall shear-rate profile at various positions before and after the rib can be measured by shifting the top wall of the

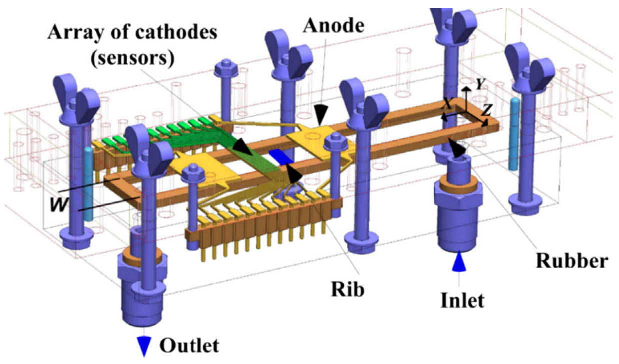

Fig. 1. 3D reconstruction of the microchannel with electrodiffusion microsensors.