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Modelling and simulation of the particle focusing behavior in microfluidic channels – effects of curvature and aspect ratio

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Abstract

Particle separation processes play an important role in medical, biological and industrial processes engineering. The present contribution employs a particle-resolving discretization of the two-phase flow using an Immersed Boundary Method to address particle separation in microfluidic channels. In particular, spiral channels are investigated, which provide substantially enhanced focusing and have been extensively analyzed experimentally. This is done by treating the equations in toroidal coordinates with a specific approximation for large radii of curvature, substantially reducing the simulation costs. The numerical scheme is successfully validated against the experimental data for rigid particles in straight and curved ducts. Then, different configurations are investigated to identify the governing parameters and their influence on the particle focusing. The new approach succeeds in capturing the relevant effects and to provide information for the design of such microfluidic spirals.

Introduction

Since the development of microfluidics a large effort was given to the separation of micro particles from polydisperse suspensions, such as observed in blood, without the use of magnetic forces or moving parts. These work continuously and do not require cleaning of any filters. The use of micro spirals facilitates the separation process by presenting a single focusing position as a result of the acting forces. Martel and Toner (2012) experimentally analyzed the migration in curved ducts and studied the focusing behavior.

The numerical analysis of this problem allows the acquisition of a large amount of information regarding the particle-flow interaction but up to now was mostly limited to straight channels (Abbas *et al.* 2014, Lashgari *et al.* 2017). The present work uses a highly efficient immersed boundary method (Kempe, Fröhlich 2012) to analyze particle migration in curved ducts and investigate the influence of curvature and aspect ratios in the focusing position.

Numerical Method

The fluid flow is modeled by the unsteady three-dimensional Navier-Stokes equations for a Newtonian fluid of constant density. The geometry of a long curved duct with a rectangular cross section lends itself to use a toroidal coordinate system, as sketched in Fig. 1 the simplified Navier-Stokes equation in this case is given by (1). The Lagrangian motion of the particle is modeled through the translational and rotational equations of motion (3), (4).

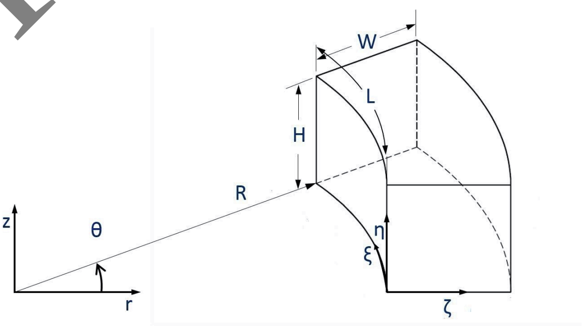

Figure 1: Curvilinear coordinate system for a curved duct.

$$\frac{\partial \boldsymbol{u}}{\partial t} + \nabla.(\boldsymbol{uu}) = -\frac{1}{\rho}\nabla p + \upsilon\nabla^2\boldsymbol{u} + \boldsymbol{f} + \boldsymbol{a_c} \tag{1}$$

$$\boldsymbol{a_c} = -\frac{uw}{R}\hat{\boldsymbol{e}}_\xi + \frac{u^2}{R}\hat{\boldsymbol{e}}_\zeta \tag{2}$$

$$m_p\frac{d\boldsymbol{u_p}}{dt} = \int_{\Gamma_p} \boldsymbol{\sigma}\cdot\boldsymbol{n}dS + V_p(\rho_p - \rho_f)\boldsymbol{g} + \boldsymbol{F_{p,c}} \tag{3}$$

$$I_p\frac{d\boldsymbol{\omega_p}}{dt} = \int_{\Gamma_p} \boldsymbol{r}\times(\boldsymbol{\sigma}^+\cdot\boldsymbol{n})dS + \boldsymbol{L_{p,c}} \tag{4}$$

$$\boldsymbol{F_{p,c}} = -\frac{m_p w_p u_p}{R}\hat{\boldsymbol{e}}_\xi + \frac{m_p {u_p}^2}{R}\hat{\boldsymbol{e}}_\zeta \tag{5}$$

$$\boldsymbol{L_{p,c}} = -\boldsymbol{I_p}\omega_\zeta \frac{u_p}{R}\hat{\boldsymbol{e}}_\xi + \boldsymbol{I_p}\omega_\xi \frac{u_p}{R}\hat{\boldsymbol{e}}_\zeta \quad (6)$$

Results and Discussion

The focusing of particle migration was validated with the results of Martel and Toner (2012) for curvature ratios of 40 and 80 with duct Reynolds numbers ranging from 50 to 200. Results showed good agreement with the experimental focusing positions and behavior, visible in the single- and double-stream focusing, as shown in Fig. 2, and also observed in the experiments.

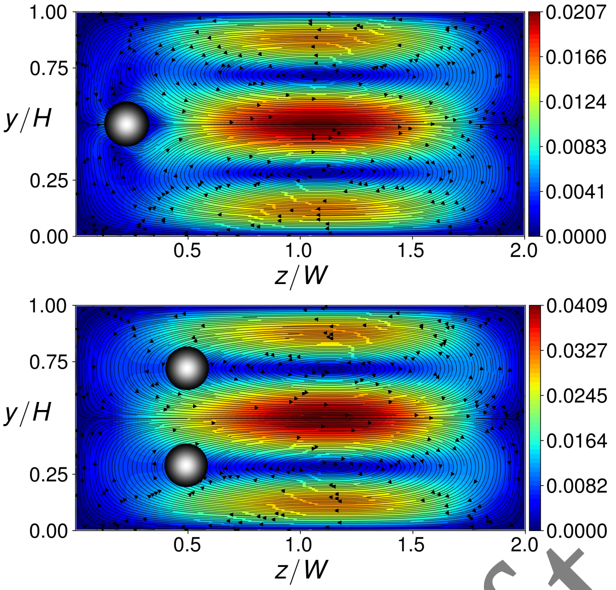

Figure 2: Mean secondary velocity contour in the cross section of a curved duct with particle focusing position at a Reynolds number of 100. Top) Single-stream focusing for curvature ratio of 80. Bottom) Double-stream focusing for curvature ratio of 40.

Simulations with different curvature ratios and aspect ratios were done. A change in the particle focusing position was observed for smaller curvature ratios with an increase in oscillation. The aspect ratio, on the other hand, showed a reduction of the particle recirculation at higher aspect ratios, due to changes observed in the Dean vortices. Stronger vortices tend to drag the particles along the channel, but an increase in the cross section aspect ratio reduces the secondary velocity near lateral walls, enabling the focusing at these positions. Fig. 3 exemplifies the interaction observed between aspect ratio and curvature.
The simulations are very costly as the physical time to be computed must be long to account for the small secondary velocity in the long spiral.

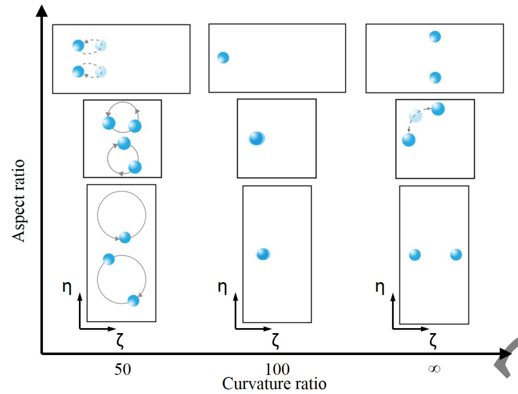

Figure 3: Particle focusing behavior as a function of curvature and aspect ratios for a channel bulk Reynolds number of 70, a constant confinement ratio and constant volume concentration of 0.3 v%. Arrows indicate particle movement in the cross section i.e. incomplete focusing. Single particles represented stable focusing conditions.

Conclusions

A modelling approach for the particle migration in curved ducts using the IBM was presented and validated at different focusing conditions. Variation of aspect ratio and curvature revealed enhanced possibilities for robust separation by the use of stable focusing conditions. These are the first simulations of their kind and provide new insight into the interaction between the particles and the impact of an increased particle concentration on focusing.

Acknowledgments

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