Modeling Inertial Focusing in Straight and Curved Microfluidic Channels

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Abstract

Introduction: Inertial focusing is a promising microfluidic technique for separating and concentrating cells of interest, processes routinely utilized in many medical procedures. This phenomenon is characterized by suspended particles in a flow spontaneously migrating across streamlines to equilibrium positions within a channel cross-section. Inertial focusing occurs due to the balance of two forces; a shear gradient lift force directed towards the channel walls and an opposing wall-interaction force. Equilibrium positions are located where these two forces balance out. In a straight channel there are two equilibrium positions as shown in Figure 1A. The equilibrium positions change with channel curvature as illustrated in Figure 1B.

The COMSOL CFD Module: We developed CFD models in COMSOL Multiphysics® to predict the equilibrium locations of the particles and their variation with flow parameters and geometry. The analysis was divided into two steps. In the first step we solve a CFD problem that does not include the particle. This gives the standard flow solutions for both straight and curved channels. We then map this solution to the inlet boundary of a second CFD model with the particle represented as a void in the CFD domain, with appropriate moving wall conditions to account for the particle's translation and rotation. Both CFD models were parameterized to facilitate the investigation of the effect of flow and geometry parameters.

The reaction forces and moments on the particle calculated from the CFD solution are used to update the particle's translational and rotational velocity components. To accomplish this, we set up global ordinary differential equations (ODEs) for the translational and rotational equilibrium of the particle. COMSOL Multiphysics solves these global equations simultaneously with the fluid dynamics equations, which significantly speeds up the solution process. When the particle reaches equilibrium we calculate the resulting transverse inertial lift forces. We then add the effect of the Dean flow, assuming Stokes drag on a particle and the Dean flow velocities obtained in the first model.

Results: The model was first validated against the established solution for straight channel flow in a 50 µm square cross section channel. We then compared the CFD model predictions to experimental measurements for straight and curved channels that are 50 µm tall, 100 µm wide and 4 cm long. Figure 2 shows experimental and simulation results for a channel Reynolds number of 100 and three Dean numbers: 0, 6 and 9 (the channel is straight when the Dean number is zero).

For each case, we show the particle distribution along the channel length collected using fluorescent streak microscopy and the force field calculated for that cross section with the equilibrium positions highlighted. The simulation results are in good agreement with experimental measurements for all three cases, and illustrate the dependence of the equilibrium positions on the channel curvature.

The ability to rapidly iterate through design changes in COMSOL Multiphysics and build a comprehensive theory for inertial focusing behavior will save experimental time as well as guide the design and optimization of life-saving diagnostic devices.

Figures used in the abstract

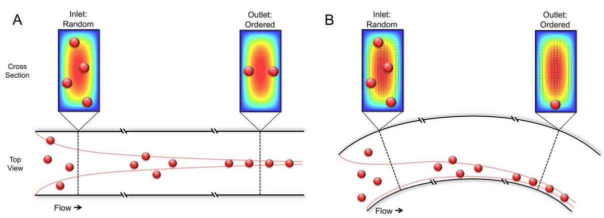

Figure 1: Effect of inertial focusing in straight (left) and curved (right) channels. Particles are randomly introduced but become ordered due to inertial focusing.

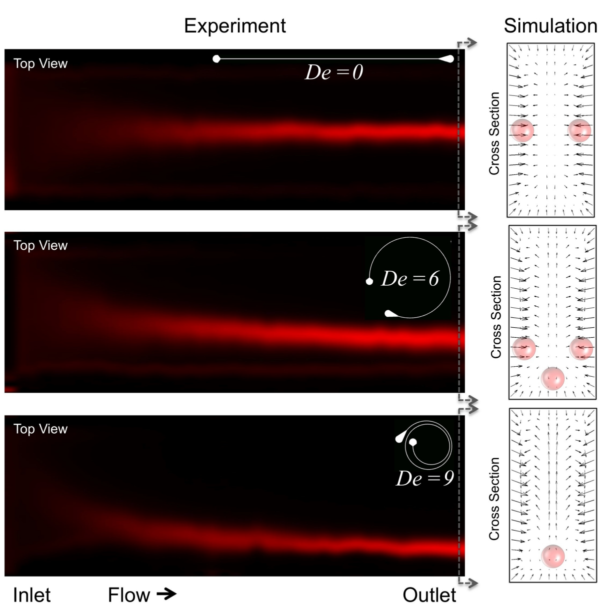

Figure 2: Experimental fluorescent microscope images (left) of the longitudinal section of the microchannels showing the distribution of particles along the channel. The cross-section plots (right) show the simulated resultant forces on the particles.