Chaotic advection using passive and actuated particles in a serpentine channel flow

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Introduction

Particulate flow at the micro scale is becoming important with the increasing interest in micro fluidic systems utilizing functional micro particles, where the particles are used as a mobile substrate for bio-assay or as stirring agents to enhance mixing. As a fundamental research on chaotic mixing in a microchannel flow with suspended particles, we investigate flow characteristics and subsequence mixing in a serpentine channel flow with passive and actuated particles. Our focus is on inducing almost global chaotic advection in this two-dimensional open channel flow by the presence and external actuation of rigid particles.

Model

Depicted in figure 1 is the geometry of the channel composed of the same repeating structure. Given the geometrical periodicity, one repeating structure is chosen as a computational domain. Flow is assumed to be governed by only viscous forces. Particles are non-Brownian and interact with fluids and other particles by hydrodynamic forces. The flow problem is solved using a fictitious domain method combined with the finite element method. In numerical simulations, use is made of a toolkit for the finite element method (TFEM).

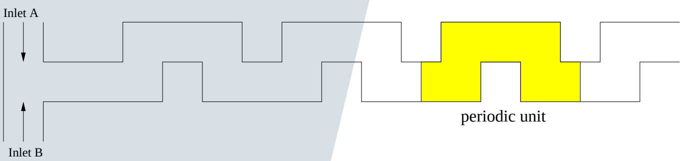

Figure 1 Channel layout of a two dimensional serpentine channel with the ratio of length to height *L*/*H*=4. Two fluids are introduced through a T-type inlet channel.

Results

Freely suspended single-particle

Particle motion is time periodic. The velocity field is time periodic as well with the same period as the particle motion. The perturbed flow around the particle is hyperbolic in nature. There are two chaotic zones separated by KAM (Kolmogorov-Arnold-Moser) boundaries along the path of the particle.

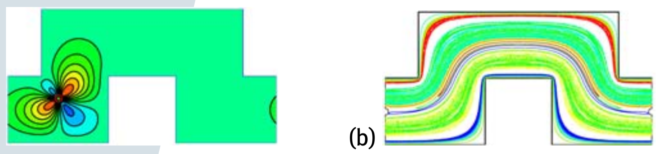

Figure 2 Single-particle problem. (a) Streamlines from the perturbed velocity $\mathbf{u}' = \mathbf{u} - \mathbf{u}_0$, where $\mathbf{u}$ is the velocity vector and $\mathbf{u}_0$ the velocity vector from the steady flow without a particle, (b) Poincaré section with different colors of passive tracers depending on their initial locations.

Freely suspended two-particle

The initial positions of the two particles are chosen to guarantee the particle motion to be time periodic. We observe hyperbolic perturbations around the particles interacting with each other and three chaotic zones separated by two paths of the particles.

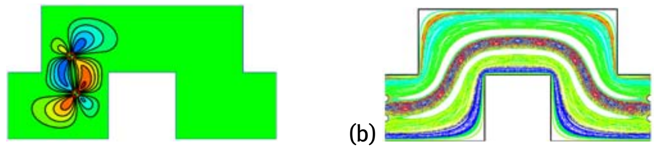

Figure 3 Two-particle problem. (a) Streamlines from the perturbed velocity $\mathbf{u}'$, (b) Poincaré section.

Actuated single-particle

We assume that a periodic external actuation of the form, $\mathbf{F} = F_0 \sin(2\pi kx/L)\mathbf{e}_y$, is applied to the particle. Here the non-dimensional force amplitude is estimated from the drag coefficient of the steady flow with a stationary circular particle. At a sufficiently high value of the non-dimensional amplitude $F_0 = 5$, almost global chaos is found except for small islands. The deformation pattern of a material strip clearly shows stretching and folding around the particle.

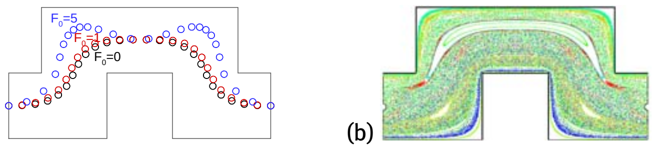

Figure 4 Actuated single-particle. (a) Particle trajectory influenced by the amplitude of non-dimensional force F_0, (b) Poincaré section with $F_0 = 5$ and $k = 2$ showing almost global chaotic advection.

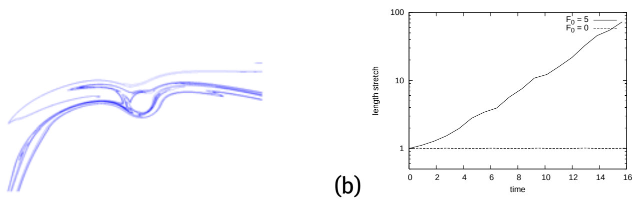

Figure 5 Deformation of a material strip with $k = 2$ and $F_0 = 5$. (a) Stretching and folding of material around the moving particle, (b) exponential length stretch as a symptom of chaotic mixing together with the Poincaré section in figure 4(b).

Conclusions

A freely suspended rigid particle acts as a moving hyperbolic perturbation and thereby induces two separated chaotic regions along the particle path. Two particles interacting with each other generate three chaotic regions along the two particle paths. The most important conclusion is that we are able to introduce almost global chaotic advection in a two-dimensional serpentine channel flow with just a single particle actuated by an external force.

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