Can Chaos Unstir Better?

CNF Project # 1278-04
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Abstract:
Irreversibility of diffusion combined with the reversibility of stirring provides interesting insights about the interplay between convection and diffusion. It has been known for a long time that stirring and un-stirring of solutes with differential diffusivities can be used to separate a mixture of solutes. Beyond speeding the separation, we ask if chaotic flows, with their characteristic amplification of error, improve selectivity relative to non-chaotic flows. In this sense, do chaotic flows un-stir better? Numerical simulations show that, no, in general chaotic flows do not un-stir better. Interestingly, the decay of reversibility and the selectivity in both chaotic and non-chaotic flows are identical with appropriately scaled times. Here, we test our results experimentally.

Summary of Research:

In Stokes regime, a non diffusive scalar can be stirred and then unstirred to its original state because of the linearity of the governing Stokes equation (1) and quasi steady state of the flow.

\[ \nabla p = \mu \nabla^2 \ddot{u}, \quad \ddot{u}(x,y,z_{\text{stir}} + z)_{\text{boundary}} = -\ddot{u}(x,y,z_{\text{stir}} - z)_{\text{boundary}} \]

where \( p \) is the pressure field, and \( \mu \) is the viscosity, \( \ddot{u} \) is the velocity of the fluid, \( z_{\text{stir}} \) is the total length of the channel where fluid is stirred, and \( z \) is axial distance along the channel (Figure 1), \( 0 < z < z_{\text{stir}} \) and \( z_{\text{stir}} = z_{\text{unstir}} \). The fore-aft symmetry of the boundary conditions along with the aforementioned linearity ensures a fore-aft symmetric flow.

In Stokes regime, when a mixture of solutes of different diffusivities is stirred in a carrier fluid for long enough, such that the solute of high diffusivity (white dots in Figure 1A) gets mixed while the solute of low diffusivity (orange dye in Figure 1A) is still stirred, then, upon un-stirring, the solute of lower diffusivity returns close to where it started, but the solute of higher diffusivity having mixed, does not return. This is the concept of Separation by Diffusive Irreversibility (SDI).

In order to experimentally demonstrate SDI, we use micro-channels with patterned floors as shown in Figure 1D and 1E, which can generate chaotic and non chaotic flows (Figure 1C). Transverse un-stirring is achieved by reversal of the groove pattern about the mid plane of the channel. Figure 1B shows the numerical simulation of cross sectional concentration profiles of solutes (red – low diffusivity, green – high diffusivity) in chaotic and non chaotic flows at the inlet, at the mid-plane (after stirring) and at the outlet (after un-stirring).

The key characteristic of the device performing SDI is that it should exhibit perfect geometric symmetry about the mid-plane of the channel (as shown in Figure 1D and Figure 1E). Another important factor is that the flow should correspond to low Reynolds number in order to remain in Stokes regime. This constraint emerges from another source of irreversibility, namely inertial irreversibility. These constraints restrain the choice of fabrication techniques.
For achieving geometric reversibility, we fabricated micro-channel in silicon using reactive ion etching using the Bosch process. The process flow for the fabrication is shown in Figure 2. It uses a two mask process, with a solid silicon oxide mask for channels, and a soft resist mask (SPR-220.3) for the channels. Once the channels are fabricated, through holes are sandblasted at the inlet of the channel for delivery of fluid. The channels are then anodically bonded to glass, and ports are stuck to the backside of the wafer. Figure 3 shows micrographs of two different trials of the fabrication taken using scanning electron microscope. Figure 3A shows groove patterns that are free of defects, and are repeatable. 3B shows defects, which can affect the geometric reversibility of the channel.

Preliminary experiments were performed with the devices with defects like the ones shown in Figure 3B to test the effect of geometric irreversibility on SDI. We were not able to test the channels without defects due to issues with bonding experiments. Fluorescein mixed with a mixture of glycerol and water served as fluid with solute of diffusivity \( \sim 10^{-5} \text{ cm}^2/\text{s} \), and the same glycerol water mixture without fluorescein serves as carrier fluid. Both the fluorescent fluid and the carrier fluid are fed into the channel side by side at Reynolds number \( \sim 0.1 \).

Confocal images of the cross-sectional concentration profiles at the inlet and outlet in Figure 4 for non chaotic flow shows the irreversibility near the floor of the channel at the end of two half cycles of stirring and two half cycles of un-stirring. For chaotic flows, we expect more irreversibility as a result of geometric imperfections because of the characteristic exponential divergence of trajectories. More experiments with lower flow speeds will help confirm that source of irreversibility is indeed geometric.

These results highlight the challenges in fabricating devices with geometrically symmetry. Further, inertial irreversibility due to non zero flow speeds can also affect separation by diffusive irreversibility. Identifying the contribution to irreversibility due to geometry, inertia and diffusion would be the key challenge in developing a working prototype of the device.

References: