MIXING AND FILTERING IN A CROSS-CHANNEL INTERSECTION

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Abstract
In the present work, a versatile microfluidic chaotic mixer using integrated actuators, has been designed and tested. It has also been characterized using theoretical modelling and simulations. The degree of control achieved within the device has led to the first observation of a novel phenomenon called spatio-temporal resonances. This phenomenon can be used to extract highly diffusive particles from a sample matrix. Experiments have successfully been compared to theory and numerics.

Keywords: Microfluidics, micromixer, PDMS, modelling

1. Introduction
In microfluidic devices, mixing primarily relies on diffusion-based motion. As a consequence, the time it would take to obtain a uniform mixing of two solutions across a microchannel, may require a long time depending on the diffusion coefficients of the molecules involved. This problem has motivated several groups, over the last few years, to design and fabricate an appreciable number of imaginative micromixers [1]. Among these, active chaotic mixers are the most efficient ones, the reason being that chaos imposes exponential growth of the contact interface between two liquids. Such mixers, if integrated into microfluidic systems, would allow compact designs to be coupled to excellent mixing. To date however, the existing active chaotic mixers are not integratable, since they use inch-size external electromagnetic actuators, interfaced with the chip [2]. In this contribution, polydimethylsiloxane (PDMS) valves were used as a means to integrate the perturbational flow control required for achieving chaotic mixing in a cross-channel intersection. The strong increase in control due to perturbation integration led to observation of a phenomenon previously unobserved.

2. Experimental
The layout of the device with its operation mode is illustrated in Figure 1. It consists of a 200-µm-wide main channel where two streams of glycerol flow side by side, one flow being marked with fluorescein and the other not. The main flow is perturbed by a transverse, oscillating periodic flow created at the cross-channel intersection. This induces chaotic-like regimes as described in Ref [2]. The oscillating flow is produced by two series of ten integrated PDMS valves displayed in a comb-shaped fashion. They were fabricated as described in Ref [3] using multilayer soft lithography technology. The basic functioning of one of the valves is explained in Figure 1. A 100-µm-wide, 26-µm-deep water-filled actuation channel compresses a 50-µm-thick membrane, closing or opening a segment of what is called here a fluidic channel. The membrane deformation will create a liquid displacement in the fluidic
channel, with a displacement amplitude depending on the applied air pressure and the valve surface area. By switching intermittently the two combs, one creates an oscillating perturbation at the cross-channel intersection. The frequency of the oscillation depends on the speed at which the two combs are switched. With this method, control of the perturbation has been found excellent for both amplitude and frequency, a feature unattainable in previous systems.

Figure 1: A) PDMS valve functioning. B) Layout of the device with operation mode. All channels are 26 μm deep. Injection flowrates are of 0.5 μL/min using syringe pumps, resulting in an average flow velocity of 3.2 mm/s in the main channel. 46% glycerol 54% water solutions were used. Fluorescent solution incorporated 1 mM fluorescein. Membrane actuation was performed using an in-house compressed-air line regulated with a manometer between 0.5 and 1 bar.

3. Theory and simulations

Theoretical and numerical study of the system yielded different regimes of mixing, depending on the amplitude and the frequency of the transverse perturbation. The two non-dimensional parameters:

\[ \alpha = \frac{A}{v} \quad \text{and} \quad \Omega = \omega \frac{L}{v} \]

where \( \alpha \) = dimensionless amplitude
\( \Omega \) = dimensionless frequency
\( A \) = perturbation amplitude
\( v \) = main flow velocity
\( L \) = perturbation channel width
\( \omega \) = perturbation frequency

fully characterize the system [4]. The system has been modelled using two 2D parabolic flow profiles flowing through the cross-channel intersection. A phase diagram of the different regimes obtained for various amplitudes \( \alpha \) and frequencies \( \Omega \) of the oscillating perturbation flow has been established.
4. Results and discussion

Figure 2 shows a snapshot of two fluids at the cross-channel intersection observed experimentally, and one produced numerically, in similar conditions. In this case, folding and stretching of material lines occurs leading to good mixing. One sees good qualitative agreement between simulation and experiment.

Figure 2: Shape of the interface at the cross-channel intersection a) experimental b) numerical simulation. Experimental conditions: flowrate 0.5 µL/min, frequency 4 Hz, air pressure 0.5 bar.

Figure 3 shows the phase diagram obtained for different values of $\alpha$ and $\Omega$. Solid contour-lines represent regimes with the same interface contact length [4]. One finds chaotic and non-chaotic regimes, separated by oak leave patterned lines. The peculiar structure of this diagram can be explained by a resonance effect which has been discovered in this research. In the chaotic regions, material lines coming out of the intersection are elongated and folded thus producing chaotic mixing.

Figure 3: Contour-plot phase diagram showing the amount of mixing as a function of the non-dimensional amplitude $\alpha$ and frequency $\Omega$, where darker gray means better mixing and visa versa. The resonances are the light spikes entering the darker region, and their theoretical predictions are the solid thick curves.

Figure 3 shows two different simulations located in different regions of the phase diagram (a and b). It is obvious in the first image (a) that for high frequencies, mixing is virtually inexistent. The second image (b) shows that strong chaotic-like mixing
with stretching and folding of material lines occurs for low frequencies with high amplitudes.

Under resonance conditions, the material lines are elongated and folded in the intersection region, but they return to their original state as they leave the intersection. Figure 4 shows the resonance phenomenon. Since this regime enhances diffusion [5], small particles located on one side of the interface will spread rapidly across the interface. The resonant regime, increasing the number of diffused particles, can be used to devise a filtering system similar to the H-filter described in Ref [6-8], with better filtering efficiency as schematically described in figure 4. In this case, the diffusional front is of about 35 μm. To obtain a similar diffusion distance for fluorescein in a 46% glycerol solution (having a diffusion constant of 7 × 10⁻⁷ cm²/s in this type of medium) without the resonance effect, one would have to wait 14 minutes and 35 seconds in similar conditions. The resonance effect could therefore be used to extract highly diffusional particles from a sample matrix with greater efficiency than existing systems.

Figure 4: Resonance phenomenon. (a) Diffusion is strongly enhanced after the channel which could allow for highly diffusional particle extraction. (b) Simulation confirms experimental. Experimental conditions: flowrate 0.5 μL/min, frequency 15 Hz, air pressure 1 bar.

5. Conclusions

In conclusion, it is possible to use this integratable versatile unit to transport, mix chaotically or filter particles, depending on the parameters actuating the oscillating transverse flow. From this viewpoint, one can consider this mixer as a “smart” versatile basic element.

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