# CHAOTIC MIXING AND RESONANCES IN A MICROFLUIDIC SYSTEM

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Microfluidic systems are too small to shelter turbulence ; thus, unlike ordinary size systems, mixing cannot bear on hydrodynamic fluctuations in microsystems. Mixing cannot rely on molecular diffusion either, because microsystems are, in many cases, too large for diffusive mixing to act as a fast process. To summarize the situation, one may say that microsystems are often inhospitable to mixing. In a standard lab on a chip device, if nothing is done, it would take hundreds of seconds to develop sequences of reactions, and this is barely compatible with the general prospective that lab-on-a chips provide fast responses to analytical concerns.

These issues were raised in the early nineties. Since then, more than twenty micromixers have been reported in the literature. [1]. The present paper is dedicated to the presentation of a particular mixer - the cross-channel micromixer (here called X-mixer) ; owing to its simplicity, this mixer may probably be viewed as representative of a broad class of active chaotic micromixers. It happens that this particular system is the host of a novel phenomenon - a spatio-temporal resonance effect - which, to the best of our knowledge, has not been noticed before. The objective of the present work is to perform an experimental study of this phenomenon.

The device was microfabricated in PDMS using two-level soft lithography technology [3]. The layout of the device, along with its operation mode, is illustrated in Figure 1. It consists of a 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 integrated PDMS valves fabricated as described in Ref [3]. The valves consist of a membrane compressing the transverse flow channels actuated by nitrogen arriving in actuation channels. The compression thus creates displacement of fluid in the transverse channels with an amplitude proportional to the surface of the actuation membrane. With this method, control of the perturbation has been found excellent for both amplitude and frequency, a feature unattainable in previous systems.

Theoretical and numerical study of the system yielded different regimes of mixing, depending on the amplitude and the frequency of the transverse perturbation. Figure 2 shows a phase diagram of the different regimes obtained for a fixed flow rate, and various amplitudes and frequencies of the oscillating flow. Solid contour-lines represent regimes with the same interface contact length. 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, as mentioned above, has been discovered in this research [5]. In the chaotic regions, material lines coming out of the intersection are elongated and folded thus producing chaotic mixing. Under resonance conditions, the material lines are elongated and folded in the intersection region, but they return to their original shape as they leave the intersection.

Figure 3 shows a snapshot of two fluids at the cross-channel intersection observed experimentally, and one produced numerically, in similar conditions, in the chaotic regime, where tendrils and whorls are produced. One sees good qualitative agreement between simulation and experiment. A similar agreement is obtained in the resonant regimes, which have been observed, in conditions consistent with the theoretical expectations.

REFERENCES

[1] D. Reyes, D. Iossifidis, P-A. Auroux, A. Manz, *Anal.Chem.*, **74**, 2623 (2002)
[2] Y.K. Lee, J. Deval, P. Tabeling, C.M. Ho, *Proc MEMS2001*, 483, Interlaken (2001)

[3] M. Unger, H. Chou, T. Thorsen, A. Sherer, S. Quake, *Science*, **288**, 113 (2000)
[4] J.M. Ottino, The kinematics of mixing, Cambridge University Press, (1989)
[5] F. Okkels, P. Tabeling, to appear in *Phys. Rev Lett.* (2004)

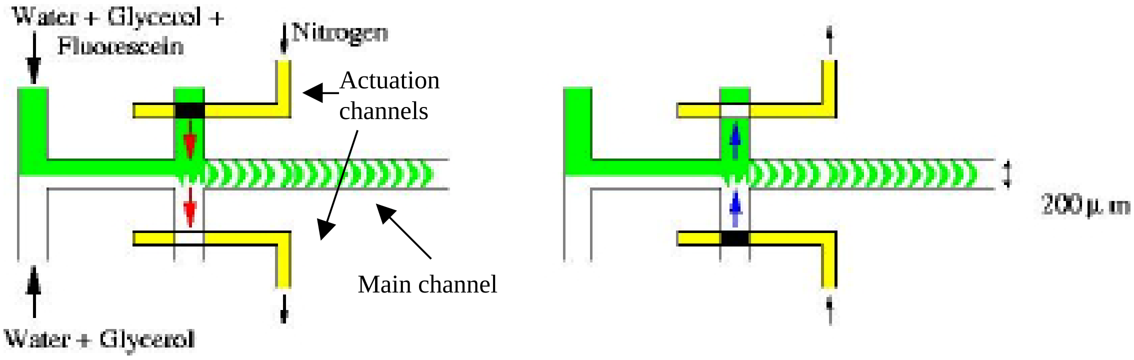



Figure 1: Layout of the device with operation mode. 46% glycerol 54% water solutions were used. Fluorescent solution incorporated 1 mM fluorescein. Membrane actuation was performed using nitrogen at 0.5 bar.

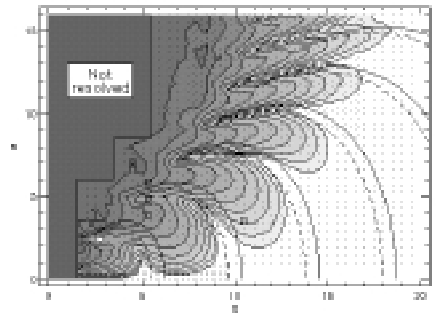
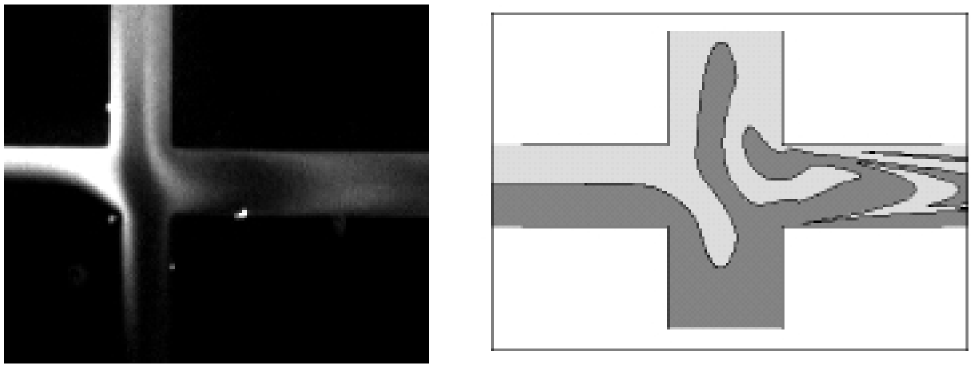



Figure 2: Contour-plot showing the amount of mixing as a function of the non-dimensional amplitude _ and frequency _, where darker gray means better mixing and visa versa. The resonances are the light spikes entering the darker region, and their theoretical predictions are the solid thick curves.



(a) (b)

Figure 3: Shape of the interface at the cross-channel intersection a) experimental b) numerical simulation. Experiment agrees with numerical simulations.