

Playing with actuators in microfluidic systems

P. Tabeling, V. Barbier, J. Goulpeau
B. Lonetti, H. Willaime,

*Microfluidics group, ESPCI, UMR7083
ESPCI, 10 rue Vauquelin, 75005 Paris (France) patrick.tabeling@espci.fr

ABSTRACT

In the labs-on-a-chip of the future, flows will be driven through mazes of microchannels and it will be crucial to integrate actuators achieving flow control ; having actuation available on-chip thus seems a condition for producing large palettes of functionalities, in a way that could bear comparison with microelectronic devices. In the present paper, we work with PDMS microfluidic systems, and the actuators are made by using multi layer soft technology [1,2]. Thus far, these actuators have mostly been used for producing valving and pumping. Here we describe different usages for these actuators : in particular, we use them for perturbing flow patterns rather than just stopping or driving fluids. This gives rise to interesting functionalities, such as mixing, extracting, building concentration gradients and controlling droplet sizes and emission frequencies.

Keywords: PDMS, actuator, MSL technology, droplet, micromixing, microfluidics.

1 BUILDING UP CONTROLLED CONCENTRATION GRADIENTS

Building up concentration gradients along microchannels is an interesting but delicate task. Most of the existing systems producing controlled concentration gradients operate normally to the flow streamlines. Operating in the longitudinal direction (with respect to the flow) imposes dealing with Taylor Aris dispersion process that efficiently works against the spatial nonuniformities of the concentration field. Here, by using actuators, we raise the control level of the system, manage to work with this process and eventually succeed to build up tuned concentration profiles with gradients directed along the flow streamlines. This is shown in Fig 1. Here the system is composed of two valves and a micro pump (see Fig 1a). The characteristics of the concentration gradient that builds up in the system is determined by the temporal sequences that are imposed at the level of the valves. In Fig 1, we show gradients of fluorescein concentration increasing with time along the channel. After a few tens seconds, we obtain well defined concentration profiles which slowly evolve in time and that can be predicted by the theory (crosses).

There is no space here to develop the theory ; it is based on Ref [3]. The idea is that, for some range of time, the tracer is well mixed in the channel height, but not in the

other directions of space. In such conditions, one can show that the concentration profile, at “large times”, is independent of the diffusion constants of the dye dispersed in the system. This means that if we deal with a mixture of solutes, the concentration profile that we produce is the same for all the constituents of the sample. Whether it is advantageous or not depends on the particular application one may consider. In any case, we do not need any calibration for anticipating the concentration profile that is produced in the device.

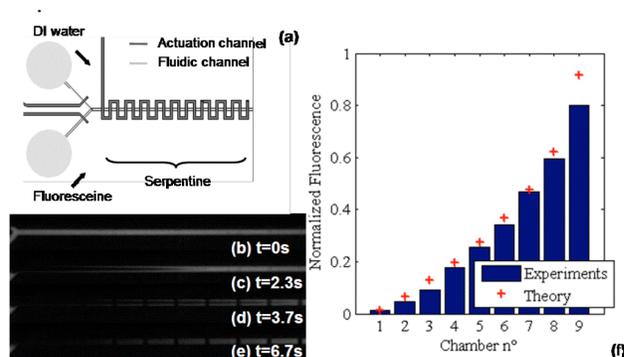


Figure 1: (a) sketch of the device. (b-e) sequence of steps leading to the formation of a longitudinal gradient (f) fluorescein concentration levels measured in the nine different chambers at time $t=6.7$ s. The crosses represent the theoretical description (Eq. 3). ($w = 200 \mu\text{m}$, $h_0 = 27 \mu\text{m}$)

2 IMPOSING DROPLET SIZES AND EMISSION FREQUENCIES

In a second example, we show actuators perturbing the droplet formation process so as to control their sizes and emission frequencies [4]. Here, the droplets are formed at the intersection of a main and a side channel. An actuator is used to modulate the flow-rate of the fluid (water) injected in the side channel. In the main channel an oil flow is driven. The actuator affects the drop formation process through a parametric resonance mechanism. In some conditions, where the coupling between the actuator and the drop formation mechanism is “strong”, one obtains frequency locking : this implies that the drop emission frequency is imposed by the actuator. In such conditions, the droplet emission frequency along with its sizes can be

varied by one order of magnitude just by changing the actuation frequency – without changing the oil or water

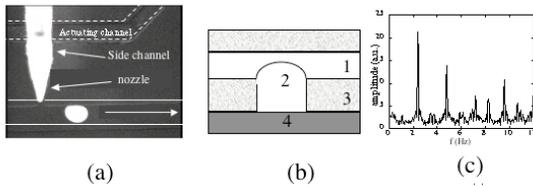


Figure 2: (a) Top view of the experiment. Tetradecane (black) and water labeled with fluorescein (white) meet in the T junction, emitting droplets. (b) Sketch of the actuation system (1) working channel; (2) actuation channel ; textured regions such as (3) : PDMS ; (4) glass substrate. The working and the actuation channel are separated by a membrane. (c) Typical Fourier power spectrum for a T junction producing droplets without actuation.

flow-rates -. This is shown in Figure 3. In other cases, the coupling is not weaker and frequency locking states are achieved in a reduced range of the actuation parameters. When synchronizaton is not obtained, we may produce chaotic-like droplets. These behaviors are well accounted for by modelling the system as a parametrically driven non linear oscillators [4]

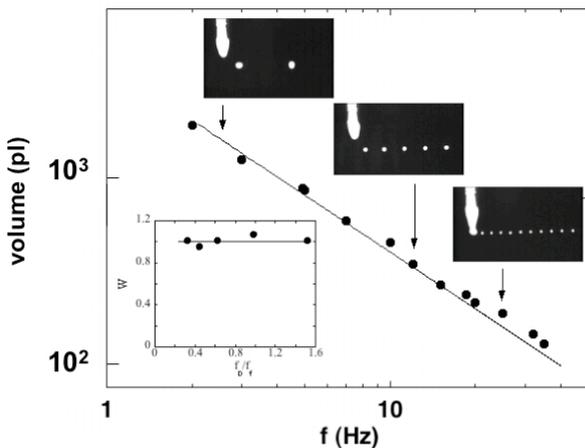


Figure 3: Evolution of the droplet volumes in function of the actuation frequency, in a 40 μm deep microchannel; oil and water flow-rates are respectively 4 and 0.1 $\mu\text{l}/\text{mn}$ and the actuation pressure P is 1.7 bar. The pictures represent droplets at various frequencies. The insert shows the evolution of the winding number with f_0/f_c , and indicates that the devil staircase includes one single step

3 - ACHIEVING MIXING AND EXTRACTION

Mixing in microsystems is a now a well documented topics [2]. Numerous micromixers have been microfabricated, and now, many options available for those desiring to mix fluids at the microscale. In the system we consider here, the mixer is a cross-channel flow system. The flow is composed of a main channel where two streams flow side by side, and a side channel developing a flow that perturbs the main stream [5] The perturbation is produced by using integrated PDMS actuators disposed onto the side channel branches. The perturbation is in form of an oscillating flow, with prescribed frequency and amplitude. By varying the amplitude and frequencies of the oscillating flow, we demonstrate that mixing can be efficiently achieved with this system. The ensemble of regimes that are obtained in this particular system are displayed in Fig 4.

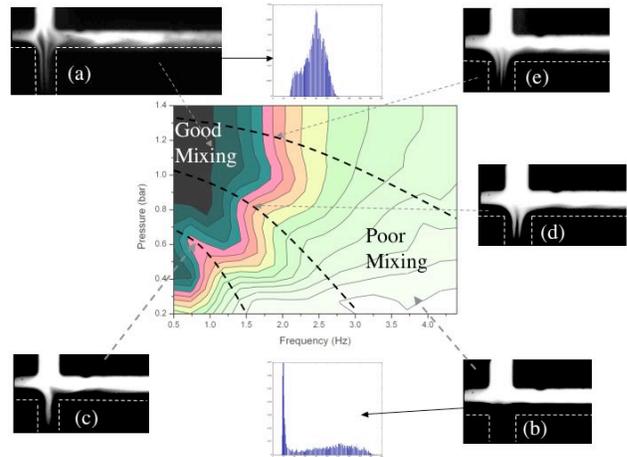


Figure 4 : Regimes observed for different actuation pressure and frequencies of the oscillating pump, acting on the side-channels. The pressure-frequency diagram is established for a fixed flow-rate, in the main channel, equal to 0.04 $\mu\text{L}/\text{min}$. The diagram represents the iso-lines of the variance σ^2 defined in the text. The scale of σ^2 levels decreases linearly from white ($\sigma^2=3000$) to black ($\sigma^2=240$). At small σ^2 one has mixing regimes, illustrated in (a). At large σ^2 (white area) we have weakly perturbed regimes, illustrated in (b). We display the concentration distributions of fluorescein, found experimentally for these two cases. The resonance regimes - i.e. those for which the interface is strongly distorted in the intersection, but returns straight again after the intersection – are illustrated in (c), (d), and (e). Resonance regimes can be classified according to the number of tendrils appearing in the intersection. One can see (c) one tendril; (d) two tendrils; (e) three tendrils. The dashed lines uncover the ensemble of the resonance conditions, as found experimentally. The detailed experimental parameters for Figs. (a–e) are the following: (a) $f=0.7$ Hz, $P=1.2$ bar; (b) $f=4.0$ Hz, $P=0.4$ bar; (c) $f=0.8$ Hz, $P=0.6$ bar; (d) $f=1.7$ Hz, $P=0.8$ bar; (e) $f=2.2$ Hz, $P=1.3$ bar. Fluorescein concentration is of 0.3 mM. Glycerol solution concentration is of 80%.

Using microactuators in this case allows to perturb the streamlines in the main channel under well controlled conditions, and thus produce, with excellent reproducibility all the regimes that one may expect theoretically. One of them is called resonance : in this case, the interface between the upper and lower fluid layer is strongly distorted in the active zone, but eventually returns straight after the intersection is passed. This regime can be used to efficiently extract small particles out of a mixture containing particles of different sizes. The principle is similar to the H filter, with an additional feature : in the resonance regimes, the diffusive processes across the interface are temporarily enhanced in the active region. This allows for obtaining rapid extraction. Thus, in the same system, by tuning frequencies and pressure applied to mechanical actuators, one may either mix or extract.

4 – CONCLUSION

Integrating actuators in a microfluidic chip certainly represents a substantial complication compared to “passive” systems, i.e those which do not possess any actuation. At the moment, most of the effort dedicated to the improvement of microfluidic system bears on passive systems. One may hope that technology will progress so as actuator integration will not represent a challenge. In this case, as shown in the present paper, a substantial number of novel functionalities will become available, facilitating the elaboration of complex systems.

REFERENCES

- [1] M. Unger, H. Chou, T. Thorsen, A. Scherer, S. Quake, *Science*, **288**, 113 (2000)
- [2] P. Tabeling, *Introduction to Microfluidics*, Oxford Univ. Press, (2005)
- [3] Ajdari, A.; Bontoux, N.; Stone, H. A. *Anal Chem* **2006**, *78*, 387-392
- [4] H. Willaime, V. Barbier, P. Tabeling, *Phys. Rev Lett*, Feb 2006
- [5] P. Tabeling, M. Chabert, A. Dodge, C. Jullien, F. Okkels, *Phil. Trans. R. Soc. Lond A* *362*, 987-1000 (2004).