Exercise 1: drop formation

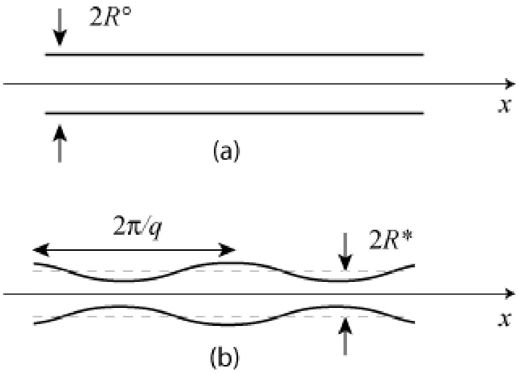
Introduction

In this exercise session, we discuss different techniques which have been used to produce micro-droplets on a controlled manner. These drops can be generated in air or in a second immiscible liquid. In microfluidics these drops are found suspended (emulsion) and can be used as micro-reactor, to follow a chemical or bio-chemical reaction, for example to screen crystallization conditions. They can also be hardened (UV polymerization, sol-gel, solvent exchange…) to produce advanced particles or capsules. In all these applications, it is crucial to control their size. The aim of this exercise session is to show that microfluidics allows obtaining very monodisperse droplets.

Rayleigh Plateau

Energy point of view - thermodynamics

We consider a cylinder of incompressible liquid (liquid 1) with a diameter R=R°. The cylinder is in suspension in a second immiscible liquid (liquid 2) as shown on the figure below. The interfacial tension between the two fluids is noted σ, the density of the fluid 1 (cylinder) is ρ and the one of the fluid 2 is ρ_{out}.



We now consider an axi-symmetric disturbance of the liquid cylinder´s radius such as: $R = R^{*} + \varepsilon \cos qx$

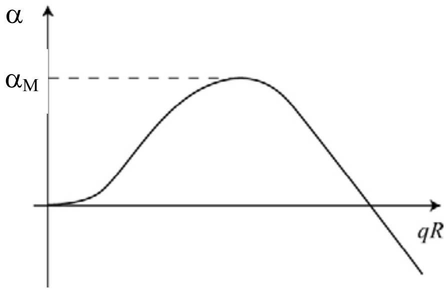
1) If the liquid is incompressible, what is the relation between R* and R° ? Under which condition the energy associated to the configuration (b) is smaller than the one of the configuration (a) - see figure above? What can you conclude from this comparison?

Mechanics point of view

2) Find the result of question 1) again using a mechanical approach. To do so, compare the pressure in bump and neck positions.

Kinetics – dynamic evolution

All disturbances do not evolve with the same kinetics. To quantify their respective kinetics, we introduce – as it is classically done – a growth rate α associated to the wave vector q ($q=2\pi/\lambda$, λ being the wavelength). The radius of the liquid cylinder thus writes: $R(x,t) = R^\circ + A \exp(\alpha\, t) \cos(qx)$



3) Comment this relation depending on the sign of α.
4) The plot representing α as a function of qR is shown here. What can you conclude from this curve?
   Using a dimensional analysis, propose an expression of α_M.
   What can you deduce regarding the drop size distribution of the drops obtained via the Rayleigh Plateau instability (inertial case)?
5) Can you propose one possible mechanism which could slow down the instability? Can you give some examples of such configurations?

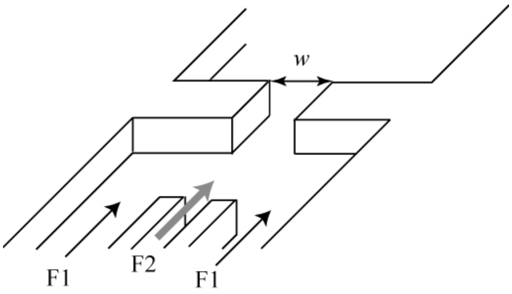
Liquid sheet confined in a channel

6) The liquid cylinder is now confined in a channel of rectangular section which sizes $L >> l$. Can this configuration be used to produce droplets? A mechanical analysis is recommended.

Microfluidics strategies

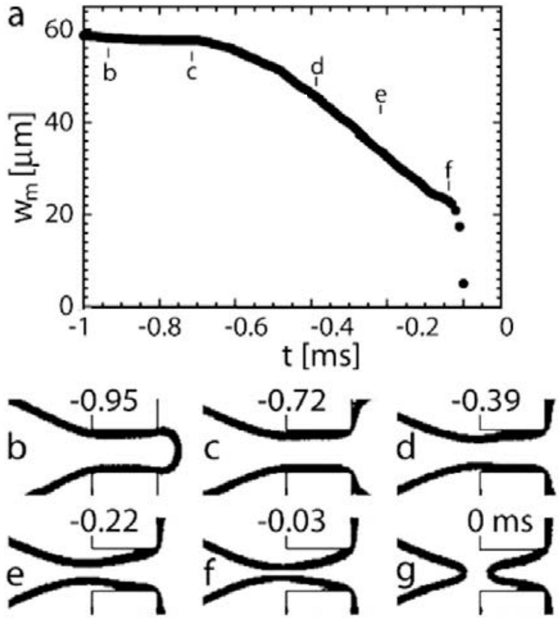
"Flow-Focusing" geometry

One of the most common geometry used to produce drops into micro-channels is the so-called "flow-focusing" geometry. As it is shown on the figure below two immiscible fluids (F1 and F2) are pushed with respective flow rates Q1 and Q2 toward a single orifice of broadness w. We note w_M the broadness of the liquid neck formed by F2 at the orifice.



7) Describe what happens at the orifice w when the stationary regime is established.

We have reproduced below the result obtained in [1]. The plot represents the temporal evolution of the broadness of the neck formed by the fluid F2 (w_M). The channels in which the fluids are confined have a depth of 30µm. The outlines drawn below the plot correspond to magnifications of the interface between the two fluids. The pictures are taken at different instant at the same position where the channel has a broadness of *w*. The letters shown on the drawing correspond to the ones of the plot.



8) Can you comment on this curve and especially on the linear decrease of w_M as a function of time for -0.6<t<-0.1?
9) Is the size distribution of the drops obtained with this set-up narrower than the one observed for non confined geometry? Estimate the characteristic standard deviation for Q1~Q2~0.5µL/s.

T-junctions

A classical microfluidic chip used in microfluidics is the so-called T junction, see sketch below. To date, two main different mechanisms of drop (or bubble) formation have been identified (left and right on the sketch).

10) One of them (squeezing) is based on the obstruction of the channel by the drop. The other one is driven by viscous shear at the interface. Could you qualitatively describe these two regimes?
11) When do you expect the transition between the two regimes to take place? Could you propose a scaling of the drop volume for squeezing mechanism?

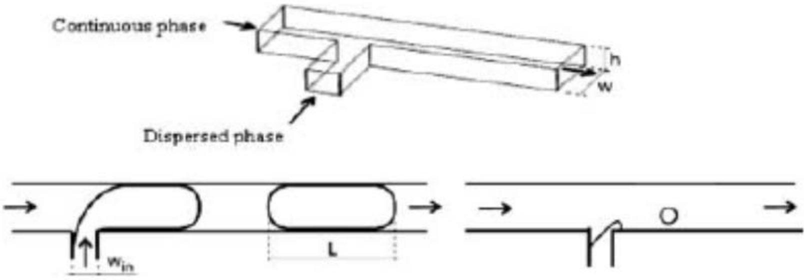


Fig. 1 A schematic illustration of the T-junction microfluidic device (Garstecki et al. 2006)

References

1) P. Garstecki, H.A. Stone, G.M. Whitesides, *Mechanism for flow-rate controlled breakup in confined geometries: A route to monodisperse emulsions* Phys. Rev. Lett. **94**, 164501 (2005)
2) P. Garstecki, M.J Fuerstman, H.A. Stone, G.M. Whitesides, *Formation of droplets and bublles in a microfluidic T-junction – scaling and mechanism of break up,* Lap Chip **6**, 437-446, (2006)
3) E. Lorenceau, Y. Yip Cheung Sang, R. Höhler, S. Cohen-Addad, *A high rate flow-focusing foam generator*, Phys. of Fluids **18**, 097103