Reynolds and Péclet Number Effects in Folding Flow Mixers

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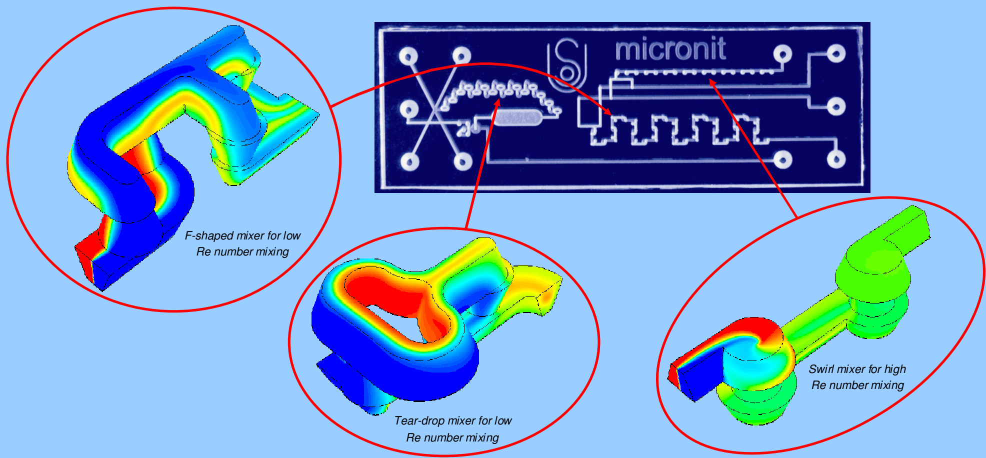
Folding Flow Mixers

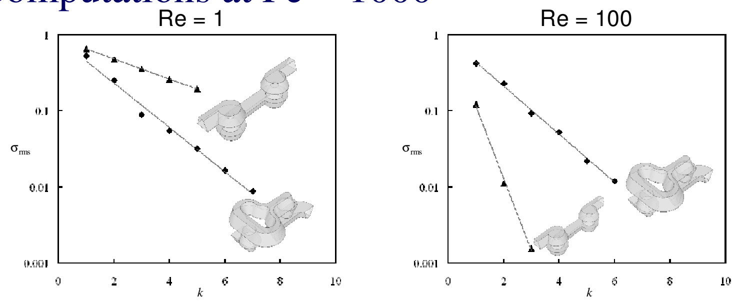
Folding flow mixers consist of a chain of elements. In each element the flow is folded upon itself, decreasing the length scale for mixing and thus reducing the mixing time. Each element has a pressure drop associated with it and therefore it is important to optimise the efficiency of the elements, the number of elements and the flowrate to achieve the desired mixing in the desired time.

The topology of a folding flow mixer varies according to whether it is designed for low or high Reynolds number (Re) flow. At low Re number, the flow is folded by the splitting and recombining of the channels. Many mixer geometries along these lines have been studied over the years, here a tear-drop shaped geometry and an F-shaped geometry (Chen and Meiners, 2004, *Appl. Phys. Lett.* **84**, 2193-2195) are investigated. At higher Re numbers, the topology of the mixer is different. In these flows, inertia can be used to fold the flow. In this work, a double swirl chamber geometry is used. The fluid spirals down through the swirl chambers, rapidly reducing the mixing length.

The mixers are all fabricated by powder blasting and thermal bonding in glass by Micronit Microfluidics (Enschede, The Netherlands).

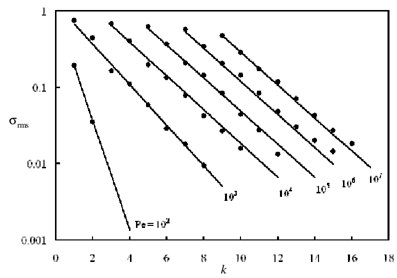


Computations at Pe = 1000



Computational Fluid Dynamics (CFD) computations can produce accurate simulations for each mixing geometry up to Pe numbers around 1000. The two plots show FLUENT computations of the number of mixer elements (k) required to produce a given rms deviation in composition (σ_{rms}). At low Re number the split and recombine topology performs better, since there is insufficient inertia in the flow for the swirl mixer to operate correctly. At higher Re number, as the inertia increases, the swirl mixer performance improves dramatically. The split and recombine topologies show small improvement at the higher Re number, but are now less efficient than the swirl mixer. The Re number will depend on the flowrate, fluid properties and channel dimensions. If higher Re number flows can be achieved, the use of a swirl mixer will dramatically reduce the number of elements required and the mixing time. However, if the inertial flow regime cannot be accessed the split and recombine topologies will provide the best mixing solution.

Pe Number Scaling

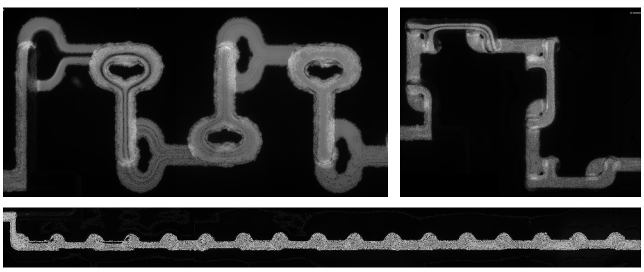


Currently, accurate computations are possible up to a Pe number of around 1000. Above this, Monte Carlo simulations can determine mixer performance. Most micro-scale mixing problems occur above a Pe number of 10^4. For folding flow mixers, a scaling law can be derived for a particular geometry (MacInnes et al, 2006, *submitted to Chem. Engng. Sci.*). The law falls into two regimes at low and high Pe number, as seen in the plot above. The dots represent CFD computations and Monte Carlo simulations in a rectilinear version of the F-shaped mixer geometry, whilst the solid lines are the scaling law derived for the same geometry. The scaling law should allow performance for this particular mixing geometry to be predicted at useful Pe numbers for mixer design.

Flow Visualisation at Pe ~ 10^5

Flow visualisation experiments can be used to obtain a qualitative insight into micro-scale mixing. The technique is based on the combination of two streams of the same fluid, one containing a fluorescent dye. Fluorescence microscopy images can then be taken to visualise the mixing of the two streams. However, the results must be used with caution. The images naturally provide depth averaged information and thus horizontal layers of unmixed fluid will appear identical to mixed fluid. This is clearly seen in every other element of the low Re number flow through the F-shaped mixer. Additionally, images taken through a curved surface may have apparent dark bands at the edges of the channel, even if the fluid there is actually dyed. This can be due to the difference in refractive index between the fluid and the glass. This effect is particularly evident here in the high Re number flows, for example through the second element of the swirl mixer. In general, visualisation experiments can provide useful supporting evidence for the computational studies above, but on their own are insufficient for a complete study of mixing effects.

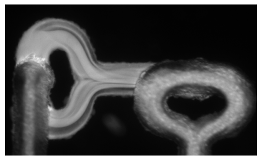
Low Re (~10^{-1}) Flow



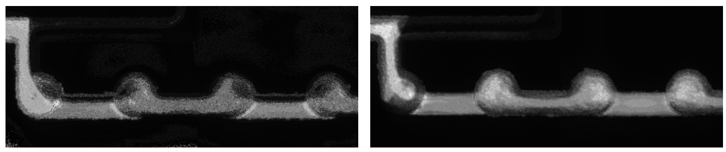
At low Re number there is no significant inertia in the flow and thus the swirl mixer is not expected to perform well. This is clearly seen in the flow visualisation experiments, with two distinct bands of dark and light fluid evident throughout the mixer. There appears to be a slow rotation of the interface along the mixer, which reduces the width of the dark band, but mixing is clearly inefficient. The split and recombine topology does effectively reduce the mixing length from element to element even at low Re number. The effect is particularly striking in the images from the tear-drop geometry where the bands are seen getting thinner and thinner from element to element. However, computations suggest that the F-shaped mixer will be slightly more efficient and there is no evidence in the images to disprove this.

High Re (~10^2) Flow

At higher Re number the flow pattern in the split and recombine topology is more complicated, with evidence of the flow twisting as it passes through the mixer. This effect is particularly striking in the first element shown here. The computations suggest that this only results in a small improvement in mixer efficiency and that the swirl mixer will be more efficient still at these Re numbers.



The Swirl Mixer



The images show the first few elements of the swirl mixer at Re = 0.25 (left) and Re = 250 (right). The effect of inertia is clearly evident with the two bands of fluid passing unaltered through the mixer at low Re number compared to a significant reduction in mixing length due to the swirl at high Re number. The computations suggest that the swirl mixer operating in the inertial regime will be the most efficient mixing solution and the evidence from the flow visualisation supports this.

Conclusions for Mixer Design

The principal constraints when designing a mixer are the flowrate required through that particular section of the micro-device, the fluid properties of the streams to be mixed and the desired level of mixing. The design variables are the channel dimensions, the number and geometry of the mixing elements and the pressure drop across the mixer. There may be additional special constraints, for example a maximum pressure or a target mixing time. It is likely that the mixing problem can be broken down into one of two forms:

1. What is the minimum pressure drop required to produce a given rms deviation in a target time?
2. For given flow conditions, what is the quickest time in which a desired rms deviation can be achieved?

The computational and experimental work here shows that the most efficient mixing solution is a swirl mixer operating in the inertial flow regime. However, if the liquid is highly viscous or the flowrate in that portion of the micro-device is low, the inertial flow regime may be inaccessible and a split and recombine topology should be used instead.

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