Slip, patterns and other small things in microfluidic systems

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Microfluidics is about flow of liquids and gases, through microdevices fabricated by MEMS (i.e. Micro ElectroMechanical Systems) technology, using hard (silicon or glass) or soft (polymers) materials. The domain is fostered by exciting applications, representing important industrial challenges. It also embraces a number of fundamental issues interesting in their own right. The introductory talk will concentrate on some of them, through a presentation of a number of experiments we have been carrying out at ESPCI, over the last three years.

Let us start with the controversial topics of slip between liquid and solid. In classical textbooks, it is considered that liquids do not slip on solid surfaces ; the so called "no-slip" boundary condition on the tangential velocity u, for ordinary liquids, has the form :

$$u=0$$

on fixed solid surfaces. This provides a fundamental condition in fluid mechanics, allowing for detailed calculations of velocity profiles and flow structures. In contrast with this picture, we now have experimental evidence that simple liquids significantly slip on atomically smooth solid surfaces and, consequently, the no-slip condition is better replaced by the more general relation:

$$u = L_S \left(\frac{\partial u}{\partial n} \right)$$

in which L_s is the extrapolation or slip length, n is the normal (inwards to the fluid). This equation – justified only with perfect gases - is called the Navier condition. The estimate of the slip length Ls is controversial at the moment. By using PIV, and working with coated non wetting smooth surfaces, Tretheway and Meinhart[(1)] measured slip lengths on the order of 1 μm. We performed similar experiments, using glass and a variety of coatings, working with wetting and non wetting surfaces, with different roughnesses[(2)]. We obtained slip lengths below 100 nm in all cases; Fig 1 shows an example where the measured slip length that we found is below 100nm, for the case of a non wetting smooth glass surface, coated with OTS, (contact angle 95°, roughness 0.31 nm). We don't know the origin of the discrepancy between these results ant those of Ref 1. In order to account for large slip lengths, one usually speculate on the existence of a thin gas layer confined between the liquid and the solid. This perhaps may reconcile the two sets of experimental observations.

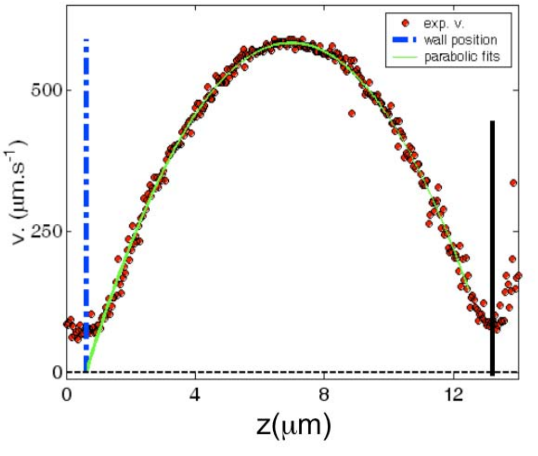

Figure 1 : Example of a velocity profile, obtained by using PIV, in a 12 µm deep microchannel (red disks). The green line is a best fit, providing a slip length equal to –35±100nm . The "foots" of the profile, within the first 400 nm close to the walls, are due to experimental errors. The data located within 400 nm is discarded in the best fit procedure.

Mixing is difficult in microsystems, and this has been a source of motivation for studying chaotic micro-mixers. We present here an experimental study of chaotic micromixing, which led to observe a novel resonance phenomenon. In this geometry, a pair of fluids flows side by side, in a channel, then pass through an intersection. At the intersection, a time-dependent flow coming from the sides is superimposed with the main stream. This additional flow perturbs the shape of the interface between the two fluids to different extents depending on the amplitude and frequency of the side-flow[(3)]. Typically, when the perturbation amplitude is small, or its frequency large, weak oscillations are generated at the interface between the pair of fluids forming the mean stream. When the amplitude is large, and the frequency moderate, stretching and folding of the interface is produced, leading to chaotic regimes. "Resonance" conditions also exist, for which the interface is strongly distorted in the active region, but returns to a flat shape afterwards. An example is shown in Fig. 2. This effect is a novel dynamical phenomenon, involving a particular interaction between space and time[(4)]. From a dynamical system viewpoint, resonant regimes are linked to the existence of KAM trajectories[(5)]. This regime can be exploited to realize an efficient micromixer/microextractor.

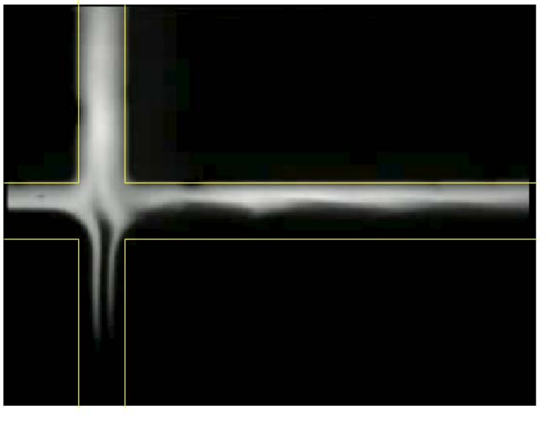

Figure 2 : In this particular case, the interface is strongly perturbed in the active zone, but returns straight as it leaves it. This is the "resonance" state. This state may be used produce efficient extraction of particles of

different sizes, forming initially an homogeneous mixture. On the picture, the width of the main channel is 200 μm, and its depth is 25 μm. A series of integrated valves produces the oscillatory flow, perturbing the main stream. The whole system is made in PDMS

The last topics deals with two-phase flows in microsystems. We consider here a miniaturized version of the tangential filter. The system is composed of a main channel, which drives most of the flow, and a side channel, through which a small fraction of the main stream is sucked. In our case we work with a two phase flows, initially composed of water drops dispersed in hexadecane[(6)]. Depending on the flow-rate conditions, drops may simply move with the main stream, or break up into two parts, each part being entrained in a different channel. In the break-up process, a filament first forms at the derivation. This filament breaks-up when it becomes too elongated (in a sense which can be made more precise by analysing in detail its geometry); an example of such a filament is given in Fig.3. The break-up conditions turned out to be well accounted for by using a theory based on Rayleigh Plateau instability.

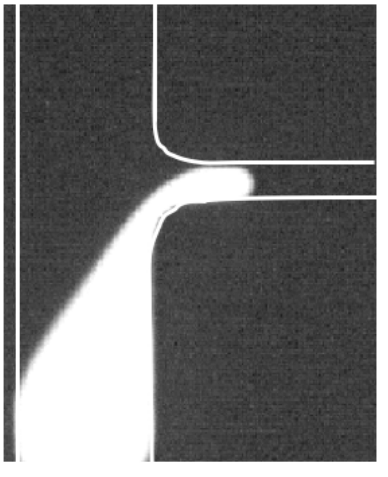

Figure 3 : Formation of a filament prior to drop break-up. The water drop (labeled with fluorescein, thus appearing as white on the picture) which is moving downwards will further split into two parts, one in the derivation channel, and the other in the main channel.

The second experiment one may mention here emphasizes on the role of the walls - a direct consequence of miniaturization - : In Ref 7, it is shown that wetting characteristics are exceedingly important in miniaturized liquid-liquid flows : depending on the wetting characteristics, one obtains well defined structures or featureless patterns, under the same flow conditions.

In conclusion, it appears through a few examples that microfluidics offers a context for the development of unfamiliar, sometimes surprising behaviors of fluid systems. Moreover, it is a often a source of inspiration for novel (micro)engineering concepts. These two aspects are discussed in more detail in Ref 8

References

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