Micro-PIV Technique – Short Overview

The PIV technique is well established for macroscopic flows. However, it has been limited to maximal spatial resolutions of 0.2 *mm* − 1 *mm* because of fundamental physical limitations, as well as practical implementation difficulties. In *Micro*-PIV, emphasis is placed on the ability to accurately and reliably measure fluid velocity with micron spatial resolution. In order to achieve microscale velocity measurements, novel developments in PIV image recording hardware, flow-tracing particles, system design, and analysis software are required [2]. The theoretical underpinnings of *Micro*-PIV are rooted in the interactions between the flow fluid and the seed particles (also named *Lagrangiane particles*) which occur at nanometer length scales. Thus, *Micro*-PIV can be thought of as a practical application of nano technology, used to perform engineering research at micrometer length scales.

The desire for high spatial resolution dictates that flow tracing particles has to be in a diameter range between 200 *nm* − 700 *nm*. Therefore, the effect of the Brownian forces on particle motion has to be taken into consideration [1]. However, an optimal particle size can be determined to obtain an accurate flow field with limited perturbation.

Advanced algorithms in post processing provide improvements in velocity accuracy and spatial resolution. The *correlation-averaging* algorithm increases virtual the effective particle concentration, while maintaining sufficiently low real particle concentration in the working fluid. Central difference interrogation procedure provides a second order estimation of velocity, which becomes important in regions containing high spatial variations in velocity. These post-processing techniques are particularly useful in challenging micro length scales and can also be extended to macroscopic flows.

In-plane spatial resolution limits

The overall goal of *Micro*-PIV technique is to obtain reliable two-dimensional velocity fields in microfluidic devices with high accuracy and high spatial resolution.

The most common mode of PIV is to record two successive images of flow tracing particles that are introduced in the working fluid, accurately following the local motion. The two particle images are separated by a known time delay, Δt. Typically, the two particle image fields are divided into uniformly spaced interrogation regions, which are cross correlated to determine the most probable local displacement of the particles. A first-order estimation of the local velocity of the fluid, $\mathbf{v}$, is then obtained by dividing the measured displacement, $\Delta \mathbf{x}$, by the time delay, Δt, between frames [1]:

$$\mathbf{v} = \frac{\Delta \mathbf{x}}{\Delta t}.$$

(1)

High spatial resolution is achieved by recording the images of flow-tracing particles with sufficiently small diameters d_p, so that they regularly follow the flow in microfluidic devices, which often exhibit high velocity gradients near flow boundaries. The particle should be imaged with the use of high numerical aperture diffraction-limited optics and a sufficiently high magnification, so that the particles are resolved with at least 3– 4 pixels per particle diameter [2]. Thus, the diffraction-limited spot size of a point source of light d_s, imaged through a circular aperture is given by [3]:

$$d_s = 2.44(M + 1)f^{\#}\lambda_1,$$

(2)

where M is the magnification, $f^{\#}$ is the *f-number* of the lens (or relative aperture), and λ_1 is the wavelength of light. For infinity-corrected microscope objective lenses, $f^{\#} \approx 1/2\left[(n_1/NA)^2 - 1\right]^{1/2}$. The numerical aperture, NA, is defined as $NA = n_1 \sin \theta_1$, where n_1 is the index of refraction of the recording medium, and θ_1 is the half-angle subtend by the aperture of the recording lens. The actual recorded image can be estimated

as the convolution of point-spread function with the geometric image. Approximating both these images as Gaussian functions, the effective image diameter d_e, can be written as:

$$d_e = [d_s^2 + M^2 d_p^2]^{1/2}.$$

(3)

Within the acquired images the obtained values of effective image diameters is of approximately 4 pixels (the interrogation areas are 32x32 pixels). This resolution is considered adequate for the microchannels used in the present experiments.

Out-of-plane spatial resolution

It is a common practice in PIV to use a sheet of light to illuminate the flow tracing particles. Mainly, the light sheet illuminates only particles contained within the depth of focus of the recording lens. This provides reasonably high quality in focus particle images to be recorded with low levels of background noise (emitted from the out-of-focus particles). The out-of-plane spatial resolution of the velocity measurements is clearly defined by the thickness of the illuminating light sheet.

Due to the small length scales associated with *Micro*-PIV, in our setup it is difficult, to form a light sheet of a few microns thick only, and even more difficult to align the light sheet with the objective lens. Consequently, it is a common practice for *Micro*-PIV to illuminate the whole test and rely on the depth of field of the lens to define the out-of-plane thickness of the measurement plane [1] (see Figure 1).
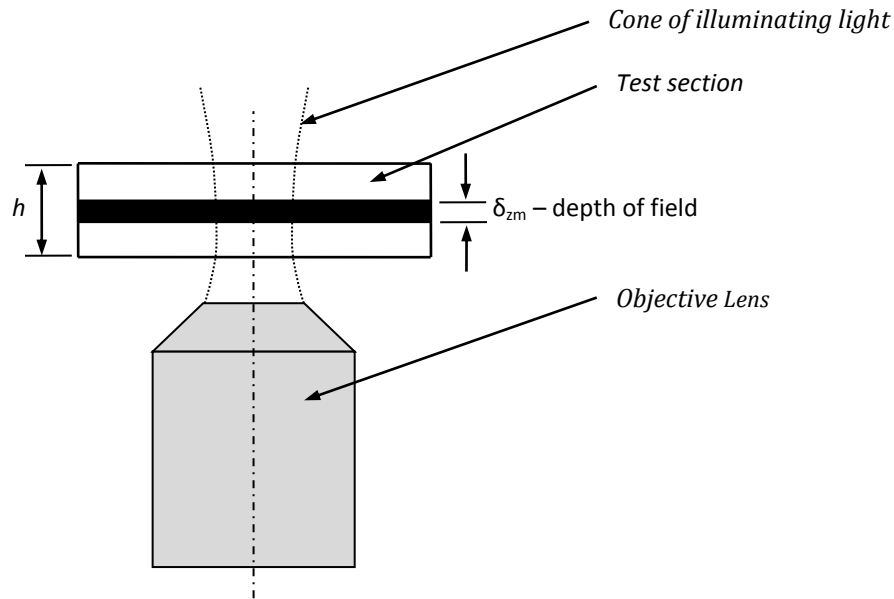

Figure 1 *Schematic showing the geometry for volume illumination particle image velocimetry.*

In this case, the expression for the depth of correlation is [2]:

$$z_{corelation} = \left[\left(\frac{1 - \sqrt{\varepsilon}}{\sqrt{\varepsilon}} \right) \left[\frac{d_p^2 [(n_1/NA)^2 - 1]}{4} + \frac{1.49(M + 1)^2 \lambda^2 [(n_1/NA)^2 - 1]^2}{4M^2} \right] \right]^{1/2}$$

(3)

where ε is chosen as 0.1.

The depth of correlation $z_{corelation}$, is strongly dependent on numerical aperture NA, and particle size d_p, and is weakly dependent upon magnification M.
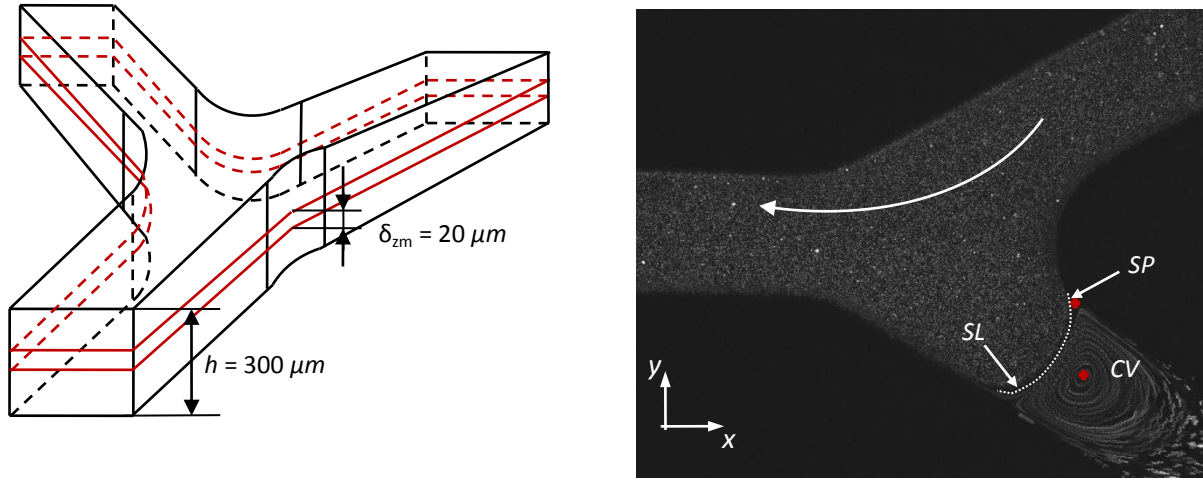

Figure 2 *The thickness of the visualized band centered in the middle of the channels depth.*

Figure 2 shows the depth of measurements $\delta_{zm} = 2z_{corelation}$ for the microfluidic devices used in the thesis. The effective diameters of the microparticles are $d_p = 0.9\,\mu m$ for the investigations performed in Y-bifurcation.

For the experimental μPIV set-ups developed in the work, the depth of fields represent 26% in the case of the Y bifurcation, from the channel height. These values have a major impact on the accuracy of measurements, so, it is expected to obtain better results in the case of the Y-bifurcation.

Hardware implementation for the μPIV system

Figure 3 shows a schematic representation of the μPIV system used for hydrodynamic quantification inside the microfluidic devices. A CCD camera (Dantec 80C77 Hisense; 1280 x 1024 pixels) with an adjustable exposure time (depending on flow conditions and the focusing region in order to satisfy the algorithm constraints) was used to acquire the images. This camera was connected to a classical microscope using a 4X and 10X magnification objective (M) with a numerical aperture of $NA = 0.1$, respectively $NA = 0.25$. Because the microdevices are made of transparent materials, it was able to illuminate the flows from below, with a micro-stroboscope laser light.
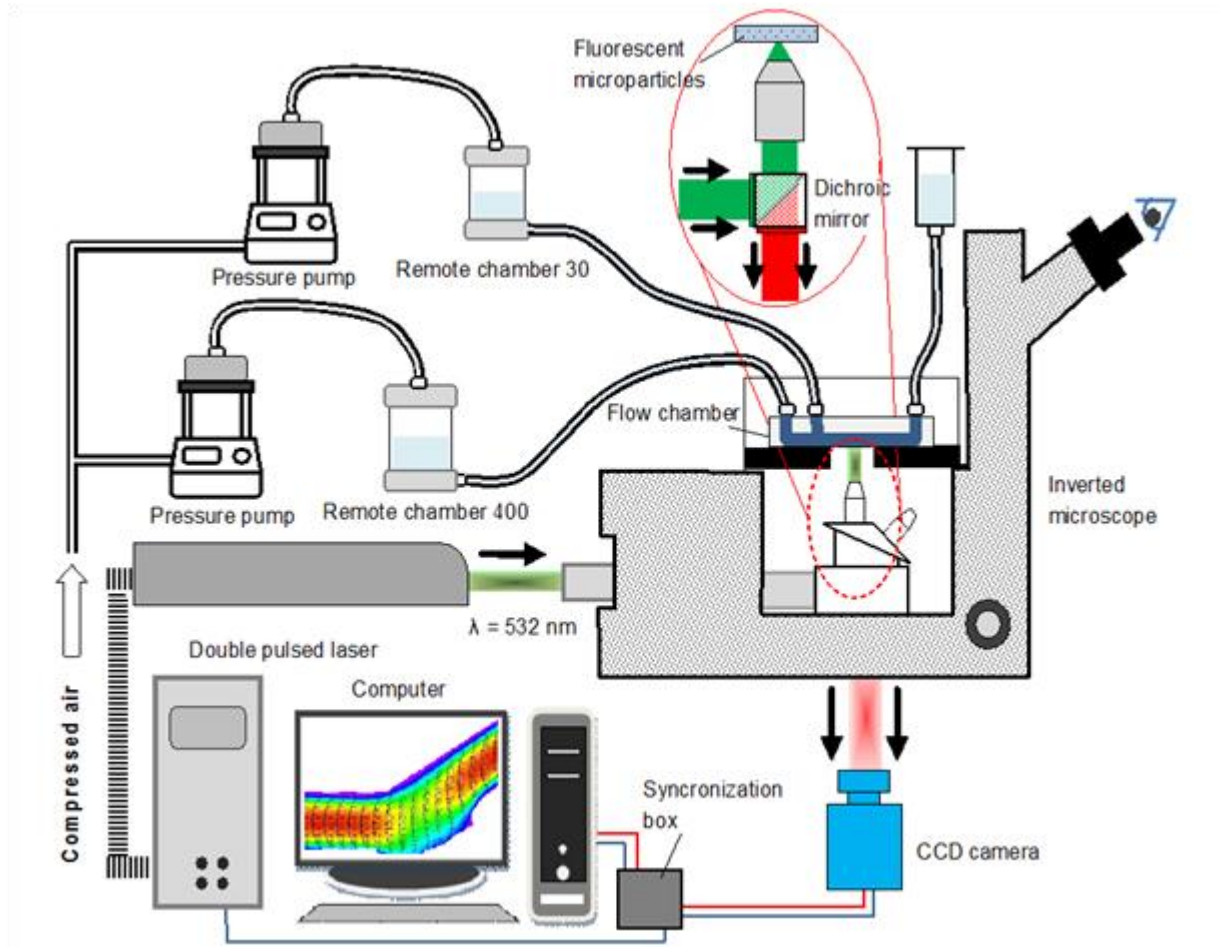
Figure 3 *Schematic representation of the µPIV measurement system. (a) - (b) experimental µPIV set-up for the microbifurcation-T; (b) - (c) experimental µPIV set-up for the microbifurcation-Y.*

In the developed experiments, a pressure gradient was imposed with a presure pump for the Y-bifurcation (see Figure 3). The working fluids are transparent and are seeded with polystyrene or silica microparticles.

The µPIV post processing results

In general, for processing are used series of 70 images of *Micro*-PIV acquisition. The working fluid from is seeded with fluorescent particles that have a diameter of $0.93\ \mu m$, in a concentration of less than 0.1%. The procedure to record the velocity vector representation is called *average-correlation*. This has the advantages of increasing the signal-to-noise ratio in the correlation function, increasing the success rate for resolving a correlation peak for each interrogation area decreasing error in the measured velocity [3].
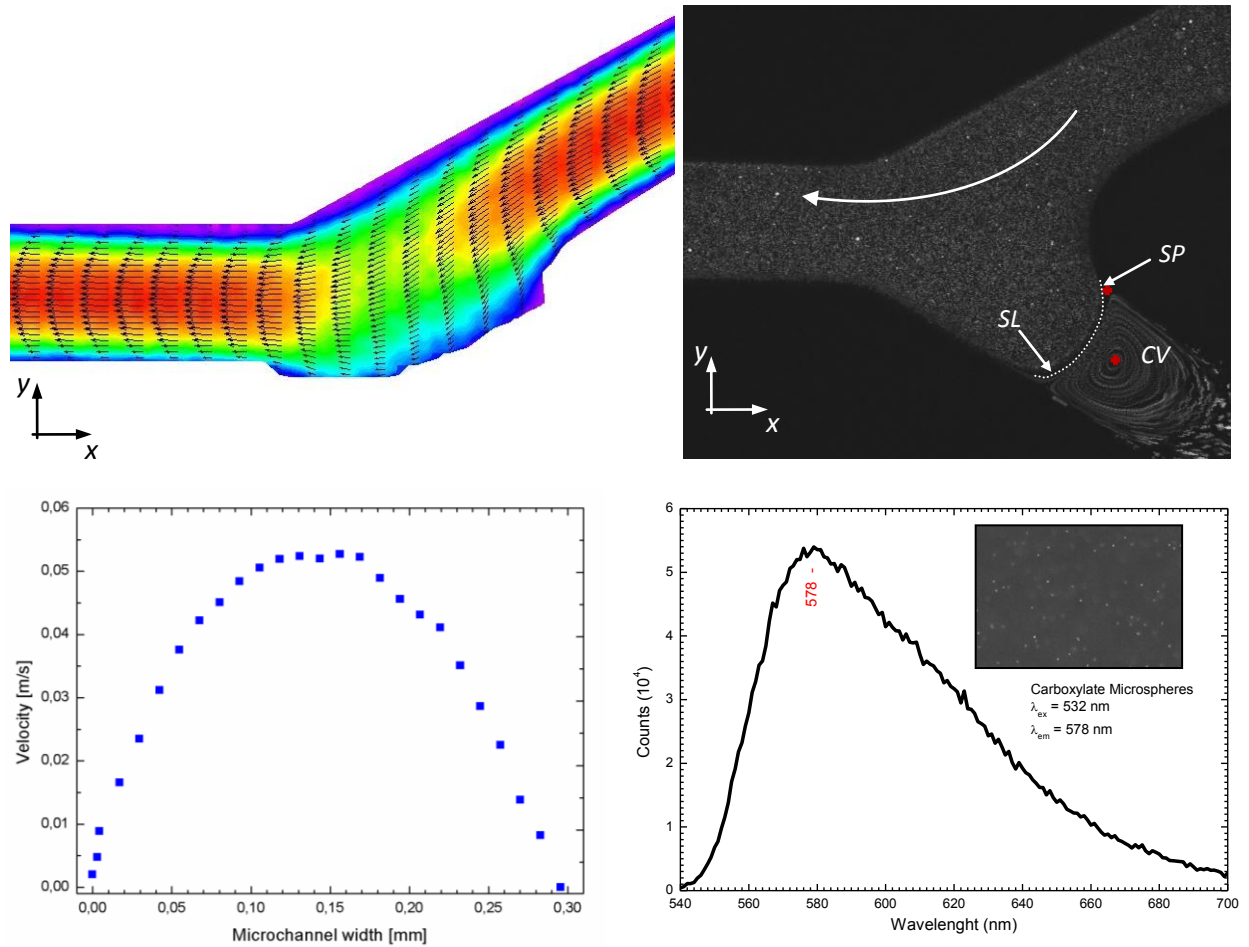
Figure 4 *Micro-PIV measurements of the velocity field and velocity profiles in the Y-bifurcation with one enter (results obtained for a Newtonian fluid; separation line SL, stagnation point SP, vortex center VC).*

The μPIV system is used in the present studies for two main goals: (*i*) to the velocity profiles in a fully developed flow (in the main flow channel), and (ii) to identify the location of the center vortex (V), stagnation point (SP) or the separation line between the main flow and the secondary one (LS). These different zones of interest are obtained by successive measurements, with a continuous control of time between the acquired images. A general image of the flow field (see Figure) is obtained by a supra-position of the interrogated areas (in the present example, 3 different measurements are considered).

Most PIV experiments do not produce feasible velocity vectors very close to the wall boundary. Hydrodynamic interactions between the particles and the wall, or background reflection from the wall overshadow particle images are "*perturbation phenomena*" which can not be avoited. It is estimated that accurate velocity mesurements are obtained within $0.5~\mu m$ from the wall.

References

[1] Meinhart C. D., Wereley S. T., Santiago J. G., 1999. *PIV measurments of a microchannel flow*, J. Experiments in Fluids 414-419

[2] Wereley S. T., Meinhart C. D., 2004. *Micron-resolution particle image velocimetry*, In: Breuer KS (ed) Microscale diagnostic techniques. Springer, Berlin.

[3] Wereley S.T., Meinhart C.D., 2003. *Micron-Resolution Particle Image Velocimetry*, http://www.engineering.ucsb.edu/~microflu/publications/Meinhart-B1.pdf.