Micro Particle Image Velocimetry – an overview

Michal M. MIELNIK[1], **Lars R. SAETRAN**[2]

ABSTRACT

We present an overview of Micro Particle Image Velocimetry (µPIV); an optical, non–intrusive measurement technique permitting detailed flow-field measurements in microfluidic devices. Both theoretical and practical issues related to µPIV are discussed, such as optical set-up, microscope objective properties, optical filters, seeding particles, particle concentration, flow illumination, system resolution, and data analysis methods. Literature overview of major work done on the subject is provided, along with application examples and potential use. Furthermore, the main limitations of the technique are pointed out.

Keywords: Micro – PIV, microfluidics, experimental

INTRODUCTION

As the emerging field of microfluidics and MEMS technology finds new and promising applications, the need to perform accurate measurements of flow parameters increases. Although the flow at microscale is typically laminar, and may thus, in principle, be readily determined by means of analytical studies and computational analysis, the complex nature of the flow poses a challenge. Three-dimensional geometries, particle-laden and multiphase flows, slip at solid walls and the combination of electrokinetic and hydrodynamic forces complicate the theoretical and computational treatment of microscale phenomena. Hence, the ability to perform measurements, not only of bulk quantities such as pressure, temperature and flow rate, but also detailed studies of the flow field inside microfluidic systems, becomes essential. Due to the small dimensions of MEMS devices, measurement techniques involving physical probes are not feasible for flow measure-

---

[1] Michal M. Mielnik, MSc – Norwegian University of Science and Technology, Dept. of Energy and Process Engineering, Kolbjorn Hejes vei 2, 7491 Trondheim, Norway.

[2] Lars R. Saetran, Prof. – Norwegian University of Science and Technology, Dept. of Energy and Process Engineering, Kolbjorn Hejes vei 2, 7491 Trondheim, Norway.

ment, and optical techniques must be applied.

Particle Image Velocimetry (PIV) is a well-established optical measurement technique for macroscopic flows, and it is extensively described in the literature (see e.g.[1], [2]). Micro-PIV (µPIV) is a modification of PIV in order to access the small scales of microfluidic devices. As pointed out by Wereley et al. [3], three major factors distinguish µPIV from its macroscopic counterpart. First, the seeding particles are small compared to the wavelength of the illuminating light, requiring the application of fluorescent imaging in µPIV. Second, due to the small particle size, Brownian motion may become a significant source of random error in measurement of the particle displacement between images, especially for slow flows. Third, and perhaps most importantly, flow illumination differs considerably. In PIV, a thin sheet of laser light is generated in order to illuminate a single plane within the fluid flow, thus defining the measurement plane of the PIV system. In µPIV, laser sheet generation is not feasible, and the entire volume of the flow is illuminated. As will be discussed later, the mode of illumination poses a major limitation on the temporal and spatial resolution of µPIV systems.

Since the development of µPIV by Santiago et al. [4] in 1998, µPIV has been applied for flow studies in microfluidic devices by an increasing number of authors. Meinhart et al. [5] studied pressure driven flow in a microchannel. µPIV measurements of the flow field in a sinusoidal microfiltration device has been reported by Mielnik and Saetran [6]. Laminar to turbulent flow transition in microtubes has recently been studied by Sharp and Adrian [7]. Klank et al. [8] applied a stereoscopic principle to µPIV to map full 3D flow-field in a chimney-structured cell sorter. µPIV has also been applied to electrokinetic flows (see e.g. [9], [10] and [11]. Recently, simultaneous velocity measurements of two liquid phases in a Y-junction microchannel were reported by Kim et al. [12]. Two-phase transient flow has been studied by Shinohara et al. [13]. Considerable effort to describe theoretically various aspects of the measurement method has been made; special interrogation techniques and filtering schemes have been developed in order to improve the quality of µPIV measurements (see e.g. [4], [14], [15] and [16]), and modifications have been attempted in order to improve the resolution of µPIV systems (see e.g. [13], [17]).

The present paper addresses the issues described above along with technical description of a typical µPIV system and its components, thus aiming to provide an overview of this rapidly growing topic.

1. µPIV SYSTEM AND OPTICAL COMPONENTS

A schematic illustration of a typical µPIV system is shown in figure 1. The system consists of a CCD camera, a microscope (upright or inverted) equipped with fluorescence filters, an external light source, and appropriate optics such as optical fibers, beam expanders, etc. The fluid inside the microfluidic device is seeded with fluorescent tracer particles which are illuminated by the light source and imaged through the microscope objective onto the CCD array of the camera.

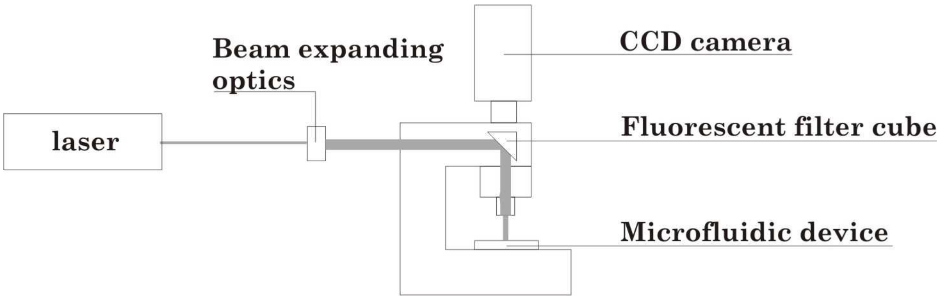

Figure 1: Schematics of a typical µPIV setup.

Illumination is commonly achieved by a double-pulsed, frequency doubled Nd:YAG laser emitting at λ_{laser}=532nm. The laser beam is delivered to the microscope directly or by means of an optical fiber. The optical fiber allows easier alignment of the light source, and, as pointed out by Devasenathipathy [9], it lowers the coherence length of the laser illumination which helps avoid speckle in particle images.

The fluorescent filter cube consists of a dichromatic mirror and an emission filter. As the laser light is monochromatic, no excitation filter is required. The dichromatic mirror is chosen such that it functions as a high-pass filter for the laser light, reflecting wavelengths below a certain pass wavelength λ_{pass}, and transmitting higher wavelengths. The emission filter serves as a high-pass filter effectively blocking any reflected laser light from entering the CCD chip, while transmitting the fluorescent signal λ_{emit} from the seeding particles. Appropriate filters and dichromatic mirrors with $\lambda_{emit} > \lambda_{pass} > \lambda_{laser}$ are available from various microscope manufacturers. As these optical components are usually designed for wavelengths matching the emission spectra of conventional continuous illumination sources such as Hg-arc lamps, mirrors and filters from laser optics manufacturers may be found more suitable. For specific examples on the choice of filters, dichroic beam splitters and particle fluorescent properties, see e.g. [6], [9]. In principle, careful choice of filtering optics may allow polychromatic µPIV, where e.g. two or more liquid phases seeded with particles with different fluorescent properties can be tracked simultaneously and independently.

A variety of objectives with different magnification levels and optical quality are applied for µPIV, depending on the size of the flow field of interest and illumination conditions. The numerical aperture (NA) of an objective is defined as $NA = n\sin\theta$, where n is the refractive index of the objective's working medium, and θ is the half-angle of the light collecting cone. NA determines the light gathering power of an objective; in an epi-fluorescent system, the image brightness (B) is proportional to the ratio between the objective's numerical aperture NA to the fourth power and the square of its magnification factor M [18]:

$$B \propto \frac{NA^4}{M^2} \tag{1}$$

Equation (1) implies that for a given level of magnification, an objective with high NA produces significantly brighter images than a low NA objective. As the fluorescent signal from the small seeding particles in µPIV is weak, high numerical aperture objectives are generally desirable due to their high light-gathering power. As will be discussed later, high NA also increases the system's resolution. For considerations of microscope objective properties with regard to efficient flow illumination, see [6].

2. SEEDING PARTICLES

A great variety of fluorescent polystyrene beads with specific gravity of approximately 1.05 g/cm^3 are available from a number of manufacturers. Particles with diameters ranging from tens of nanometers up to several microns, and fluorescent properties covering a vast range of excitation and emission wavelengths, are off-the-shelf products. The requirement that particles faithfully follow the flow (small particle diameter) and have a density closely matching that of the suspending fluid is not difficult to satisfy for liquid flows. In addition, the particles should be large enough to dampen the effects of Brownian motion, and to provide a sufficiently strong fluorescent signal. For gas flows, the challenges of seeding particles suitable for microfluidic devices have not yet been overcome.

When seed particles become sufficiently small, particle – fluid interactions give rise to random particle movement, preventing the particles to follow the flow faithfully. The effects of Brownian motion on µPIV measurements were considered by Santiago et al. [3]. With D being the Stokes-Einstein diffusion coefficient of a particle suspended in a fluid moving at a uniform velocity u, the relative error ε_B in the measured particle displacement during a time interval Δt may be estimated as:

$$\varepsilon_B = {}^1\!/_u \sqrt{{}^{2D}\!/_{\Delta t}} \tag{2}$$

Equation 2 shows that the effect of Brownian motion becomes of lesser importance as the flow velocity increases. Furthermore, as the diffusion coefficient D is proportional to fluid temperature and inversely proportional to particle diameter, the error increases with both rising temperature and smaller particle diameters. Also, the error due to Brownian motion is seen to decrease with increasing time of travel, Δt. The latter, however, is limited by spatial resolution issues such as interrogation window size.

The error arising from Brownian motion is random in nature, and may be considerably reduced by averaging over a population of particles. In µPIV, each interrogation window usually contains an insufficient amount of particles, and it is common practice to perform ensemble averaging over several realizations in order to achieve satisfactory correlation, leading to substantial reduction in the overall error. Assuming each particle to be statistically independent, and each realization to be sampled at statistically independent times, the uncertainty due to Brownian motion of the ensemble averaged velocity field may be approximated as $\varepsilon_B/N^{1/2}$, where N is the total number of particles in the average [3]. For a detailed treatment of Brownian motion and its influence on velocity measurement in µPIV, the reader is referred to [19].

4. RESOLUTION AND ACCURACY

The resolution of any optical system is limited by diffraction [18]. In µPIV, this limit is posed by the diameter d_s of the central ring (Airy ring) in the diffraction pattern formed by the fluorescent particles. When imaging circular, self-luminous objects, the diameter of the point-spread function is given by:

$$d_S = 2.44M \frac{\lambda}{2NA} \tag{3}$$

where M is the magnification, λ is the wavelength and NA is the numerical aperture of the objective [20]. Equation 3 implies that high NA results in smaller point-spread function diameter, which in turn increases the resolution of the optical system. The diameter of the image recorded by the CCD array is a convolution of the diffraction-limited and geometrical image, and can be approximated by $d_e=[M^2d_p^2 + d_s^2]^{1/2}$, where d_e is the effective image diameter and d_p is the particle diameter [2].

Due to the mode of flow illumination in µPIV, the measurement plane thickness (the out-of-plane resolution) of the system is solely determined by the optical characteristics of the imaging optics. The focal depth of the microscope objective is not an accurate estimate of the out-of-plane resolution, as particles in vicinity of the focal plane also contribute to the correlation peak. The measurement depth of a µPIV system was defined by Meinhart et al. [21] as twice the distance from the object plane to a location such that the imaged particle is sufficiently unfocused, so that it does not significantly contribute to the velocity measurement. The particle image intensity when this occurs is set to 10% of the maximum intensity of a focused particle, yielding the following expression:

$$\delta z_m = \frac{3n\lambda_o}{NA^2} + \frac{2.16 d_p}{\tan\theta} + d_p \quad (4)$$

where δz_m is the measurement depth, n is the refractive index of the imaging medium, λ_o is the wavelength of the imaged light in vacuum, and θ is the light collecting angle of the objective [21]. For low magnification - low NA objectives, the measurement depth may impose a considerable degree of volume integration on µPIV velocity measurements. Recently, two promising efforts have been reported on decreasing δz_m, one by application of a power-filter to µPIV images, and another by modification of the µPIV setup [14], [17].

One important consequence of volume illumination is the fact that all particles in the illuminated fluid volume emit light, not only those residing within the focal plane of the imaging optics. Particles outside the focal plane create a background noise and thus reduce the Signal-to-Noise Ratio (SNR) of the particle images. Meinhart et al. [21] identified two prime parameters influencing SNR, namely particle concentration and test-section depth. They measured the SNR for four different channel depths and four different particle concentrations, showing that higher SNR can be obtained by either reducing the channel depth or the particle concentration. A summary of their findings is shown in table 1.

Table 1

SNR of the in-focus particle-image field for various particle concentrations and test – section depth.

Test-section depth (µm)	Particle concentration (by volume)			
	0.01%	0.02%	0.04%	0.08%
25	2.2	2.1	2.0	1.9
50	1.9	1.7	1.4	1.2
125	1.5	1.4	1.2	1.1
170	1.3	1.2	1.1	1.0

In cases where the microchannel of interest is designed to serve a certain microfluidic purpose, the geometrical dimensions of the channel are predefined and hence the channel depth cannot be altered. Particle concentration is then the only adjustable parameter.

From table 1 it is apparent that particle concentration must be kept low in order to obtain defined particle images for deep channels, generally resulting in images with insufficient number of particles for conventional correlation-based interrogation techniques. In order to overcome this limitation, average correlation is commonly applied in µPIV, where the correlation functions from a series of image pairs are averaged prior to detection of the correlation peak ([5], [16]). Another method, not requiring modifications to PIV interrogation software, is the ensemble averaging, or addition of individual image pairs prior to interrogation [6]. The number of image pairs is chosen such that the resulting image pair has a sufficiently high number of particles for standard interrogation schemes. For a more thorough discussion of interrogation techniques in µPIV, see [3].

The low particle density in µPIV recordings poses a major restriction on the temporal resolution of µPIV, as only time-averaged velocity data are obtainable. The averaging techniques for interrogation described above rely on the inherent assumption of time-independent, laminar flow. Even though this is indeed often the case on the microscale, a variety of transient flow phenomena occur in two-phase flows, electrokinetic flows and mixing. High-speed µPIV measurement of transient flow has recently been reported by Shinohara et al. [13]. Using a continuous wave laser for flow illumination and a high-speed camera (2000 fps) equipped with an image intensifier, instantaneous velocity fields in a micro counter-current flow were captured at 500 µs time resolution. The channel depth was 25µm, permitting sufficiently high seeding concentration for standard interrogation techniques to be applied.

5. CONCLUDING REMARKS

Micro Particle Image Velocimetry permits detailed flow-field measurements in microfluidic devices. The technique has experienced a rapid development and gained popularity during the past few years. Although µPIV theory and technical aspects are largely established and standardized, significant improvements both in statistical interrogation techniques and image processing, along with hardware modifications and novel applications continue to appear in the literature. The major limitations of the technique lie currently within temporal- and out-of-plane resolution of the systems, making measurements generally restricted to stationary velocity fields, often with significant volume-averaging. These limitations are already being addressed by the µPIV community, and will certainly continue to be addressed in the future.

ACKNOWLEDGEMENTS

This work is supported by The Research Council of Norway, project number 147028, and by the Norwegian University of Science and Technology (NTNU).

REFERENCES

1. Raffel, M., Willert, C., and Kompenhans, J., 1998, *Particle Image Velocimetry; A Practical Guide,* Springer – Verlag, 3rd edition.
2. Adrian, R. J., 1991, Particle – imaging techniques for experimental fluid mechanics, *Annu. Rev. Fluid Mech*., Vol. 23, pp. 261-304.

3. Wereley, S.T., Gui, L., Meinhart, C.D., 2002, Advanced algorithms for microscale particle image velocimetry, *AIAA Journal*, Vol. 40, No. 6, pp. 1047-1055.
4. Santiago, J. G., Wereley, S. T., Meinhart, C. D., Beebe, D. J., Adrian, R. J., 1998, A particle image velocimetry system for microfluidics, *Experiments in Fluids*, Vol. 25, pp. 316-319.
5. Meinhart, C. D., Wereley, S. T., Santiago, J. G., 1999, PIV measurements of a microchannel flow, Experiments in Fluids, Vol. 27, pp. 414-419.
6. Mielnik, M., Saetran, L., 2003, Micro-PIV investigation of a crossflow microfiltration module, *Proc. 1st Intl. Conf. On Microchannels and Minichannels*, Rochester NY, USA, pp. 887-894.
7. Sharp. K.V., Adrian, R.J., 2004, Transition from laminar to turbulent flow in liquid filled microtubes, *Experiments in Fluids*, Vol. 36, pp. 741-747.
8. Klank, H., Goranovic, G., Kutter, J.P., Gjelstrup, H., Michelsen, J., Westergaard, C.H., 2002, PIV measurements in a microfluidic 3D-sheathing structure with three-dimensional flow behaviour, *J. Micromech. Microeng.*, Vol. 12, pp. 862-869.
9. Devasenathipathy, S., Santiago, J.G., 2002, Particle tracking techniques for electrokinetic microchannel flows, *Anal. Chem.*, Vol. 74, pp. 3704-3713.
10. Devasenathipathy, S., Santiago, J.G., Wereley, S.T., Meinhart, C.D., Takehara, K., 2003, Particle imaging techniques for microfabricated fluidic systems, *Experiments in Fluids*, Vol. 36, pp. 504-514.
11. Meinhart, C.D., Wang, D., Turner, K., 2003, Measurement of AC electrokinetic flows, *Biomedical Microdevices*, Vol. 5, pp. 139-145.
12. Kim, B.J., Liu, Y.Z., Sung, H.J., 2004, Micro PIV measurement of two-fluid flow with different refractive indices, *Meas. Sci. Technol.*, Vol. 15, pp. 1097-1103.
13. Shinohara, K., Sugii, Y., Aota, A., Hibara, A., Tokeshi, M., Kitamori, T., Okamoto, K., 2004, High-speed micro-PIV measurement of transient flow in microfluidic devices, *Meas. Sci. Technol.*, Vol. 15, pp. 1965-1970.
14. Bourdon, C.J., Olsen, M.G., Gorby, A.D., 2004, Power-filter technique for modifying depth of correlation in microPIV experiments, *Experiments in Fluids*, Vol. 37, pp. 263-271.
15. Wereley, S.T., Meinhart, C.D., 2001, Adaptive second-order accurate particle image velocimetry, *Experiments in Fluids*, Vol. 31, pp. 258-268.
16. Meinhart, C.D., Wereley, S.T., Santiago, J.G., 2000, A PIV algorithm for estimating time-averaged velocity fields, *Journal of Fluids Engineering*, Vol. 122, pp. 285-289.
17. Park, S.J., Choi, C.K., Kihm, K.D., 2004, Optically sliced micro-PIV using confocal laser scanning microscopy (CLSM), *Experiments in Fluids*, Vol. 37, pp. 105-119.
18. Inoue, S., Spring, K.R., 1997, *Video microscopy: the fundamentals*, Plenum Press, 2nd edition.
19. Olsen, M.G., Adrian, R.J., 2000, Brownian motion and correlation in particle image velocimetry, *Optics & Laser Technology*, Vol. 32, pp. 621-627.
20. Born, M., Wolf, E., 1999, *Principles of Optics*, 7th edition, Plenum Press, New York.
21. Meinhart, C.D., Wereley, S.T., Gray, M.H.B., 2000, Volume illumination for two-dimensional particle image velocimetry, *Meas. Sci. Technol.*, Vol. 11, pp. 809-814.